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SATELLITE & MESOMETEOROLOGY RESEARCH PROJECT

Department of the Geophysical Sciences

✓ The University of Chicago

✓ NCR-14-00-008

BASIC PROBLEMS ON CLOUD IDENTIFICATION
RELATED TO THE DESIGN OF
SMS - GOES SPIN SCAN RADIOMETERS

by

Tetsuya Theodore Fujita

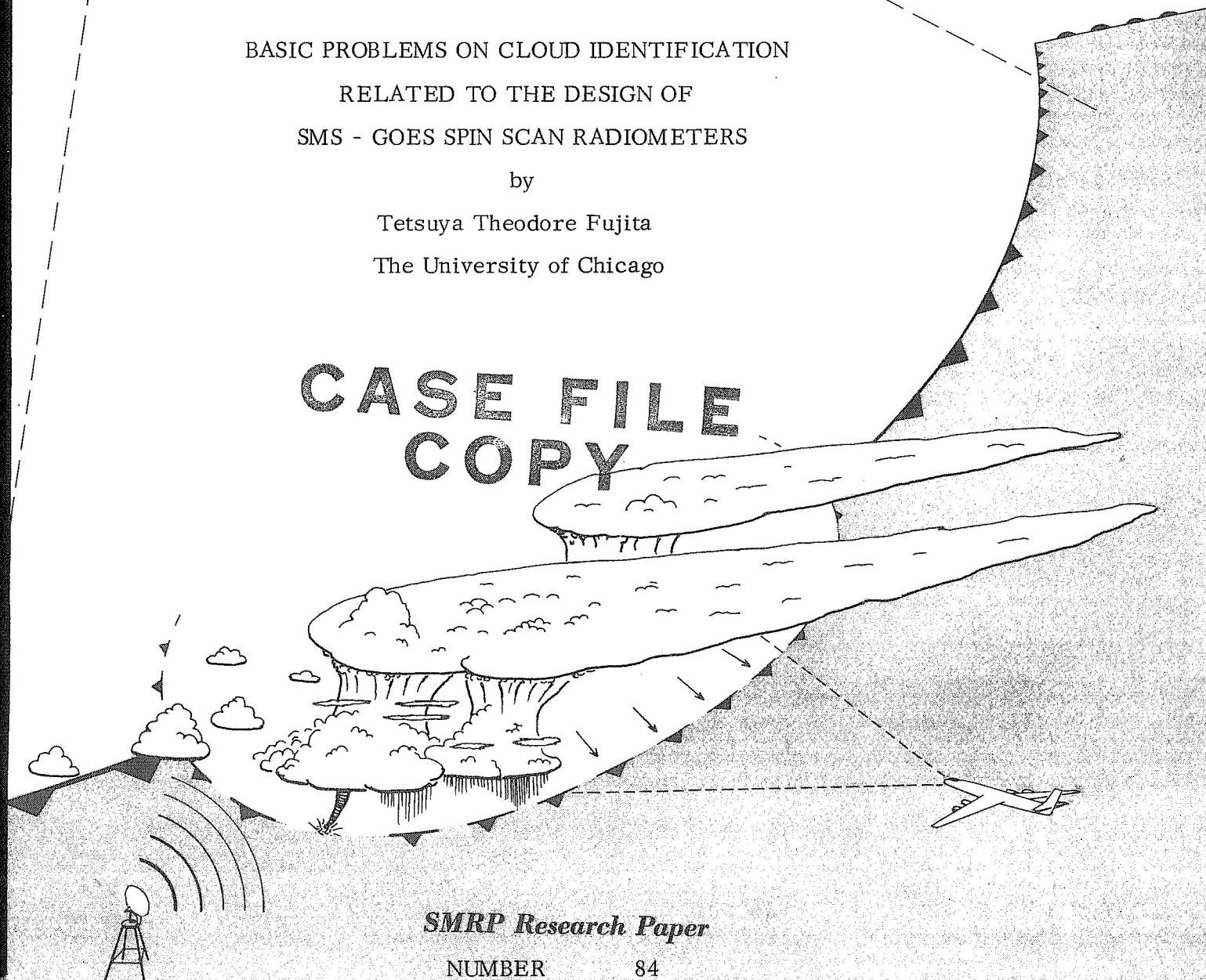
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ABSTRACT

To determine design criteria for future geostationary satellites, meteorological input based upon up-to-date knowledge of nephosystems will be useful. This study compiled under NASA Grant NGR-14-001-008 was requested by Mr. W. R. Bandeen on December 19, 1969. The subjects discussed in this paper are: horizontal resolution, picture intervals and areas, brightness and radiance enhancement. Unbiased recommendations were made based upon meteorological evidences obtained by the author as of January 1970.

1. Introduction and Summary

While spin scan cloud cameras are being experimented with on board ATS I and III, it would be worthwhile to evaluate future possibilities of utilizing spin scan radiometers for meteorological purposes. Basic design parameters related directly to meteorological applications are:

- (1) Horizontal Resolution
- (2) Picture Intervals and Areas
- (3) Brightness and Radiance Enhancement.

Of these, the last item of enhancement is to be performed on the ground if unsaturated signals with proper dynamical range can be recorded on master telemetry tapes.

(1) HORIZONTAL RESOLUTION

Unless an extreme resolution better than 0.1 or 0.2 miles can be achieved, a picture or a series of pictures can not be used for visual identification of cloud types or for cloud-height computations from cloud and shadow relationships (refer to Apollo pictures in Figs. 8 and 13 both with a 0.1 mile or better resolution). These Apollo pictures were degraded until clouds became too fuzzy to be identified in terms of their types. When the resolution is worse than 0.3 miles most cirrus clouds lose their identity.

The traceable mean life of convective cells increases with the cloud diameter. Clouds with a 2-3 mile diameter will have only a 23-min half-life which is too short for a tracing period. Larger clouds with much longer traceable life extend through deep layers. Their motion does not represent flows within a thin layer. Moreover, their motion is affected by cloud characteristics which could cause considerable deviation in the cloud motion from the mean flow velocity. It is thus recommended that convective cells of 4 to 10-miles in diameter be used as tracers (refer to Figs. 6 and 7 showing the cloud life). In order to allow for the detection of these tracer clouds within 80% of the picture disc, a 2-mile IFOV at the subsatellite point is recommended.

The traceable mean life of cirrus clouds is usually much longer than that of convective cells. A similar size to that of convective cells is recommended in relation to the research described in Section 2.

When two cloud bands each with a one-mile width are scanned with a 2-mile IFOV, they can be identified when they are separated only as far as three quarters of a mile. Under favorable circumstances a radiometer can detect patterns much smaller than IFOV (refer to Fig. 21).

For the infrared radiometer a 0.25 mr IFOV is recommended as long as we are bound to use the present $NE\Delta T$. For single cloud detection a larger IFOV is better. When twin or multiple clouds related to severe storms are scanned, however, it is necessary to reduce IFOV to 0.25 or 0.20 mr in order to avoid smearing effects (refer to Figs. 24 and 26 dealing with $SC\Delta T$ and $TC\Delta T$).

Ideally, a 0.10 mr infrared IFOV which is identical to a recommended

2-mile visible IFOV is highly recommended. Combinations of both IR and visible measurement will permit us to compute emissitivity and cloud height. Meanwhile such a small IFOV will permit us to detect cells of severe storms at their early stages of development.

(2) PICTURE INTERVALS AND AREAS

For tracing slow-moving clouds including tropical cumulus cells and stratus cells which move with a speed less than 30 kt, picture intervals of 20 to 30 minutes are sufficient.

Cells of jetstream cirrus or overshooting clouds around hurricane centers require more frequent pictures. A 5-minute interval is recommended for tracing these clouds. A method of local scan must be devised to achieve such a frequent picture acquisition (refer to Figs. 12 and 15).

For IR pictures it is recommended that full-disc pictures are taken at 20-to-30-minute intervals during two periods 1100 to 1300 GMT and 2300 to 0100 GMT daily for wind velocity estimations.

(3) BRIGHTNESS AND RADIANCE ENHANCEMENT

This subject was first tested with Hurricane Camille pictures. Further research will be necessary to achieve effective enhancement taking solar zenith and azimuth angles into consideration (refer to Figs. 18 and 19).

The establishment of ground equipment for rapid production of enhanced pictures for operational uses is recommended.

2. Life of Convective Clouds as Tracers

An ideal tracer floating in the atmosphere is like a group of molecules floating inside the free atmosphere. A convective cloud always undergoes processes in which the cloud loses some molecules while gaining certain others. In order to estimate the environmental flow from cloud motion, it is better to select small clouds with insignificant vertical growth. In reality, however, it is necessary to select those tracer clouds whose

life is long enough to be followed for velocity determinations. At the present time there are no statistical studies relating cloud life to type and environment.

A pilot study was made by selecting an area to the southeast of Hurricane Gladys on October 17, 1968. As shown in an Apollo-7 picture (see Fig. 1) looking southeast from a 184-km altitude, the area extending from Miami, Key West to Havana was characterized by cumulus to towering cumulus clouds extending up to approximately 7 km MSL.

An enlarged ATS III picture in Fig. 2 taken about 4 hours after the Apollo picture shows the same cloud band as that seen in the Apollo picture. A corresponding radar picture taken by WSR-57 radar at Key West is shown in Fig. 3. To assist the comparison of radar echoes and corresponding clouds in these pictures, both latitudes and longitudes were drawn at one-degree intervals. The resolution of the radar picture, about 1 to 2 miles, is better than the 3- to 4-mile resolution of the ATS cloud patterns. Careful examination, however, reveals a good correspondence between echo cells and cellular clouds.

In order to investigate the life of clouds to be used as tracers, the life of a cloud is defined as the period between the initial and last picture showing the cloud. In most cases the cloud in the initial picture can be traced back in several pictures taken prior to the initial picture. Now we shall define

t_F = Picture time of the first cloud or the picture time of the first appearance of a cloud to be traced in an ATS picture series.

t_O = Time of the initial picture or the time of the first picture in the series used for the cloud-velocity computation.

t_L = Picture time of the last cloud or the time of the last appearance of a traced cloud in an ATS picture sequence.

If the picture interval is much shorter than the cloud life we may express the total life of a cloud by

$$L_j = (t_L - t_F)_j \quad (1)$$

The mean total life can, therefore, be written as

$$\bar{L} = \frac{1}{N} \sum_1^N L_j = \frac{1}{N} \sum_1^N (t_L - t_F)_j, \quad (2)$$

where N is the number of clouds selected in the initial picture.

When clouds are used as tracers, they are to be followed in successive pictures from the initial picture rather than from the picture showing the first cloud. In most cases there are no useable pictures prior to the initial picture of the cloud-motion computation, thus nothing is known about the condition of the same clouds prior to the initial picture time, t_0 .

The mean traceable life $\bar{L}_{TR}$ can be defined in a similar manner to that of the mean total life in Eq. (2), thus

$$\bar{L}_{TR} = \frac{1}{N} \sum_1^N L_j = \frac{1}{N} \sum_1^N (t_L - t_0)_j \quad (3)$$

where N is the same number of clouds used in Eq. (2) and j designates the identical cloud in Eq. (2). It is seen that the difference between the mean total life and the traceable cloud life is

$$\begin{aligned} \bar{L} - \bar{L}_{TR} &= \frac{1}{N} \left\{ \sum_1^N (t_L)_j - \sum_1^N (t_F)_j - \sum_1^N (t_L)_j + \sum_1^N (t_0)_j \right\} \\ &= \frac{1}{N} \sum_1^N (t_0 - t_F)_j \\ &\cong \frac{1}{N} \sum_1^N (t_L - t_0)_j = \bar{L}_{TR} \end{aligned} \quad (4)$$

because the time of the initial picture is selected independently from the life period of each cloud appearing in the initial picture. We will, thus, find that the mean traceable life is one-half of the mean total life of clouds. Namely the equation is written

$$\bar{L}_{TR} = \frac{1}{2} \bar{L} \quad (5)$$

In order to determine the life of an individual cloud selected in the initial picture taken at t_0 , cellular clouds in Fig. 2 were numbered 1 to 129 (see Fig. 4). If all of these 129 clouds were found in successive pictures, all can be used as tracers during the entire picture period. In reality, however, the number of surviving clouds decreases with a higher picture number or decreases with the time past the initial picture.

We write the surviving cloud number, $N_0, N_1, N_2, N_3, \dots, N_n$, seen on successive pictures taken at $t_0, t_1, t_2, t_3, \dots, t_n$, where N_0 denotes the number of clouds selected in the initial picture taken at t_0 . Since we do not add new clouds in successive pictures while losing clouds of initial selection, N decreases with increasing picture time. Now the mean life of traceable clouds can be expressed in the following form,

$$\begin{aligned} \bar{L}_{TR} &= \frac{1}{N_0} \left\{ (t_1 - t_0)(N_1 - N_2) + (t_2 - t_1)(N_2 - N_3) + \dots \right\} \\ &= \frac{1}{N_0} \left\{ N_1(t_1 - t_0) + N_2(t_2 - t_1) + \dots \right\} \\ &= \frac{\Delta t}{N_0} \sum_{i=1}^n N_i \end{aligned} \quad (6)$$

where $\Delta t = (t_1 - t_0) = (t_2 - t_1) \dots$ is the time between successive pictures assumed to be constant. By shortening the picture interval Δt to dt , we are able to express the mean traceable life by

$$\bar{L}_{TR} = \frac{1}{N_0} \int_{t_0}^{t_n} N dt \quad (7)$$

where t_n is the time of the last picture in a sequence. Since N varies with cloud diameter, D , we may define $N(D)$ as the cloud number sorted against the cloud diameters. Then

we rewrite Eq. (7) as

$$\bar{L}_{TR(D)} = \frac{1}{N_{O(D)}} \int_{t_0}^{t_n} N_{(D)} dt . \quad (8)$$

If we assume an exponential function

$$N_{(D)} = N_{O(D)} e^{-K_D(t-t_0)}$$

to represent the number of clouds, we are able to integrate the right side of Eq. (8), thus

$$\bar{L}_{TR(D)} = + \frac{1}{K_D} \left\{ 1 - e^{-K_D(t_n-t_0)} \right\}$$

which can be reduced to

$$\bar{L}_{TR(D)} = \frac{1}{K_D} \quad (9)$$

when $(t_n - t_0)$, the picture-taking period is very long.

The half-life of clouds, $t_{\frac{1}{2}}$, as defined by

$$\frac{1}{2} N_{O(D)} = N_{O(D)} e^{-K_D t_{1/2}}$$

is obtained by taking the logarithms of both sides, thus we have

$$\log 2 = K_D t_{1/2} \log e$$

or

$$t_{1/2(D)} = \frac{1}{K_D} \frac{\log 2}{\log e} = 0.693 \frac{1}{K_D}$$

or

$$\bar{L}_{TR(D)} = 1.44 t_{1/2(D)} \quad (10)$$

Eq. (10) reveals that the mean life of traceable clouds is 1.44 times the half-life of traceable clouds.

In order to find out the half-life of clouds in Fig. 4 as a function of the cloud diameter they were sorted according to their diameters measured in the initial picture

taken at 1922 GMT, Oct. 17, 1968. Each cloud may undergo diameter changes during its tracing period but the initial diameter was used as the basis of sorting. At 2017 GMT when the third picture (see Fig. 5) was taken individual clouds changed considerably while overall hurricane patterns remained almost unchanged. Such a change in individual clouds can be revealed only by tracking individual cells from one frame to the next with extreme care.

The normalized cloud population as a function of the time after the initial count at 1922 GMT is shown in Fig. 6. To avoid undesirable scatter resulting from the small number of clouds entered in these statistics, cloud diameters were put together into 2-3, 4-6, 7-9, and 10-13 nautical miles. Four curves, which are more or less exponential, indicate that the larger the initial cloud diameter the longer the cloud lives. Their half-life measured at the intersection of decay curves with the 50% line reveals that the half-life of the 2-3 mile clouds is only about 23 min or its mean traceable life is $1.44 \times 23 = 33$ minutes while for clouds with a 10-13 mile diameter, the half-life increases to 60 minutes.

Shown in Fig. 7 is the half-life of traceable clouds given as a function of the cloud diameter. The curve starts from the natural origin, where $D = 0$ and $t_{\frac{1}{2}} = 0$ and increases gradually to about 50 min for clouds that are 10 miles in diameter. From this example it may be concluded that the population of tracer clouds decreases at a rate where the proper selection of cloud size and picture interval is necessary.

RECOMMENDED FURTHER RESEARCH

(a) Further Study of the Life of Tracer Clouds.

The life of tracer clouds varies according to 1) cloud types, 2) vertical wind shear inside the cloud layer, 3) cloud diameter and other parameters. When the vertical wind shear is very weak, such as in the central region of large anticyclones, even a small convective cloud can be traced for several hours. It would be necessary to complete a statistical study of cloud life taking the various parameters into consideration.

(b) Study of Ambient Wind Velocity in Relation to Satellite-Measured Cloud Motion.

The fact that the larger the cloud diameter the longer the cloud life does not mean that large clouds should be used for cloud-motion and subsequent wind-velocity determination. Large clouds are more likely to move differently from the wind velocity at a given level. Even a concept of steering flow is not applicable to large clouds. Basic research on cloud motion is, thus required.

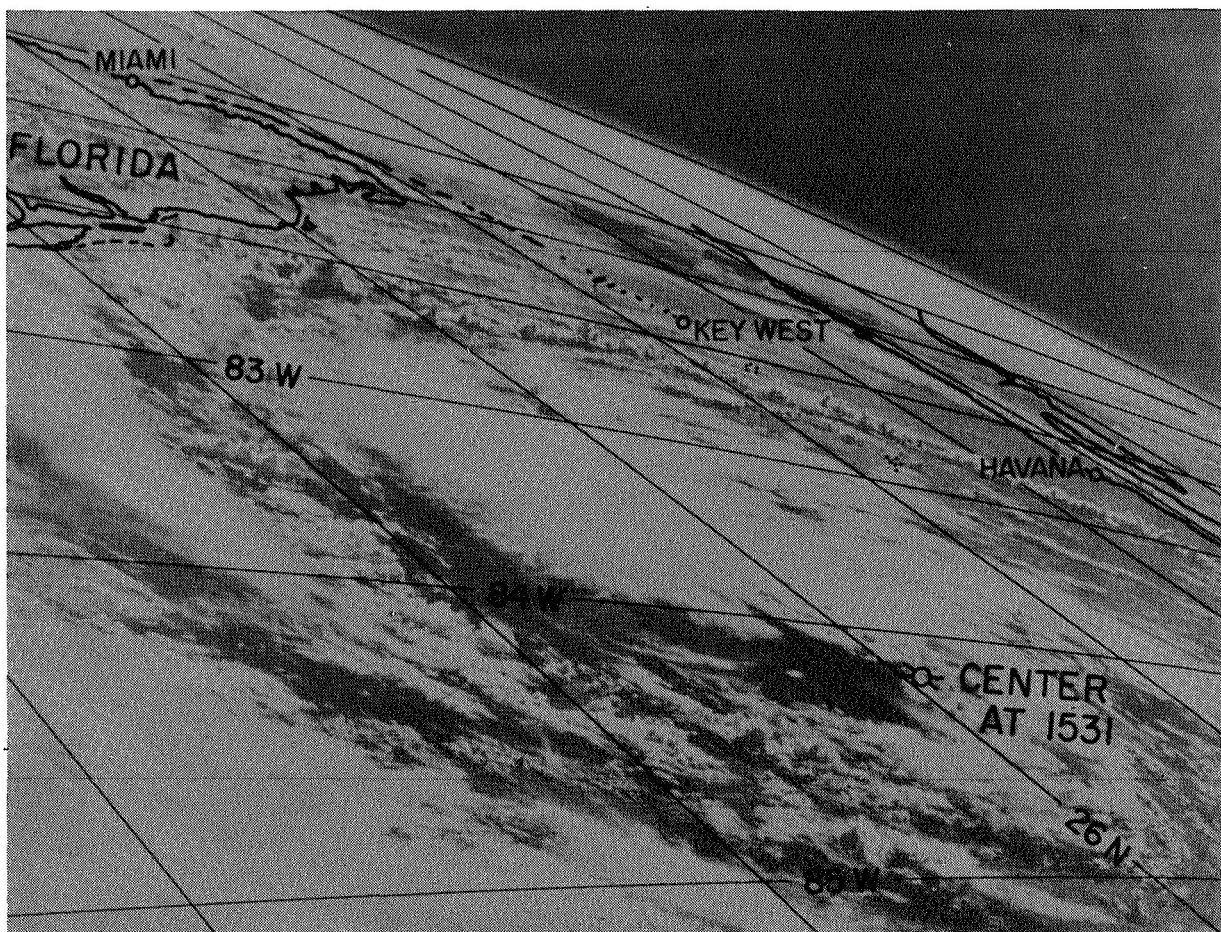


Fig. 1. An Apollo 7 view of Hurricane Gladys of October 17, 1968. The picture was taken at 1531 GMT from 184-km altitude looking southeast. The life of convective clouds in the southeast sector of the storm was studied. This Apollo picture reveals that convective clouds in this sector consist mainly of cumuli extending up to 7 km.

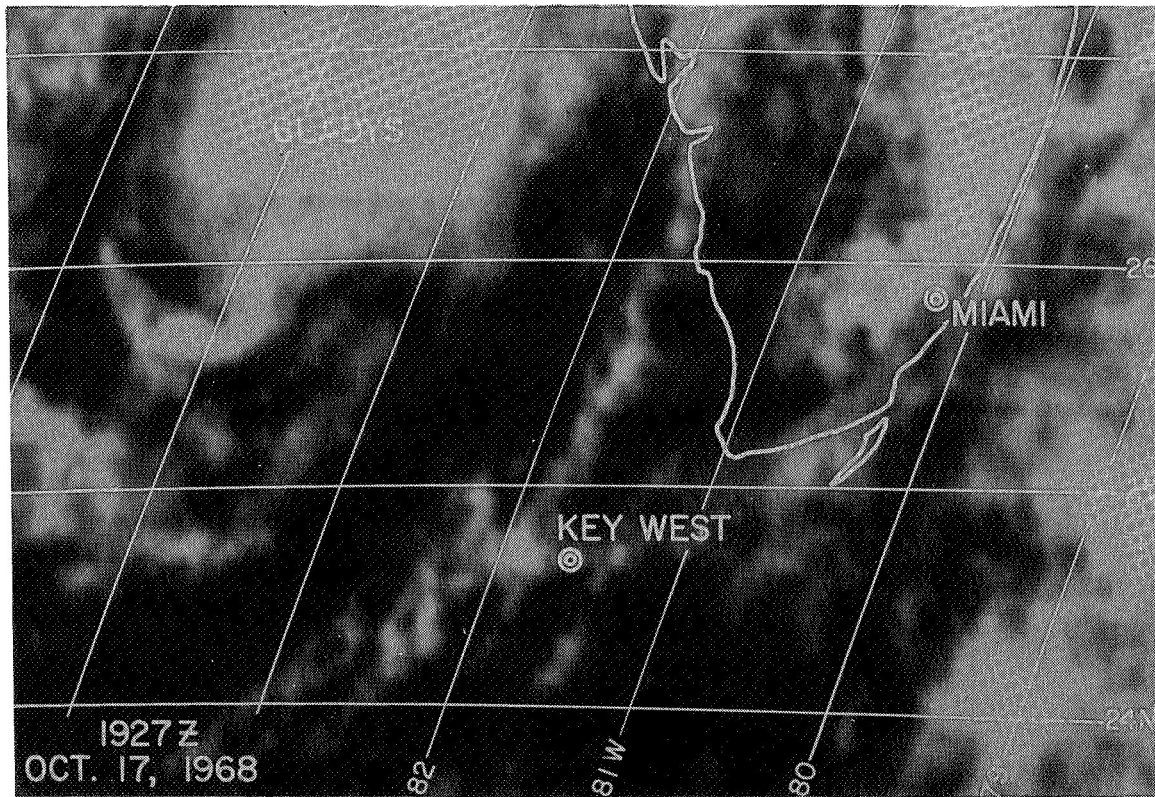


Fig. 2. The initial ATS III picture of cloud-life determination. The picture taken at 1927 GMT was gridded at one-degree intervals.

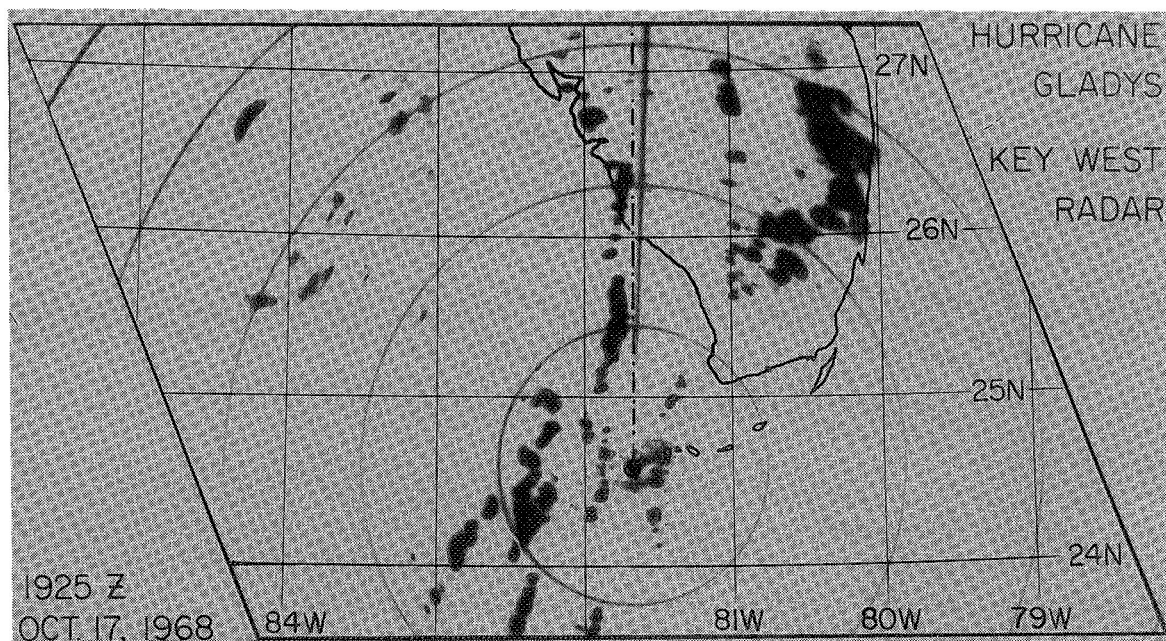


Fig. 3. A PPI scope picture obtained by a WSR-57 radar at Key West, Florida. The area of this radar picture is identical to that of the ATS III picture in Fig. 2. Range markers are at 50 n.m. intervals.

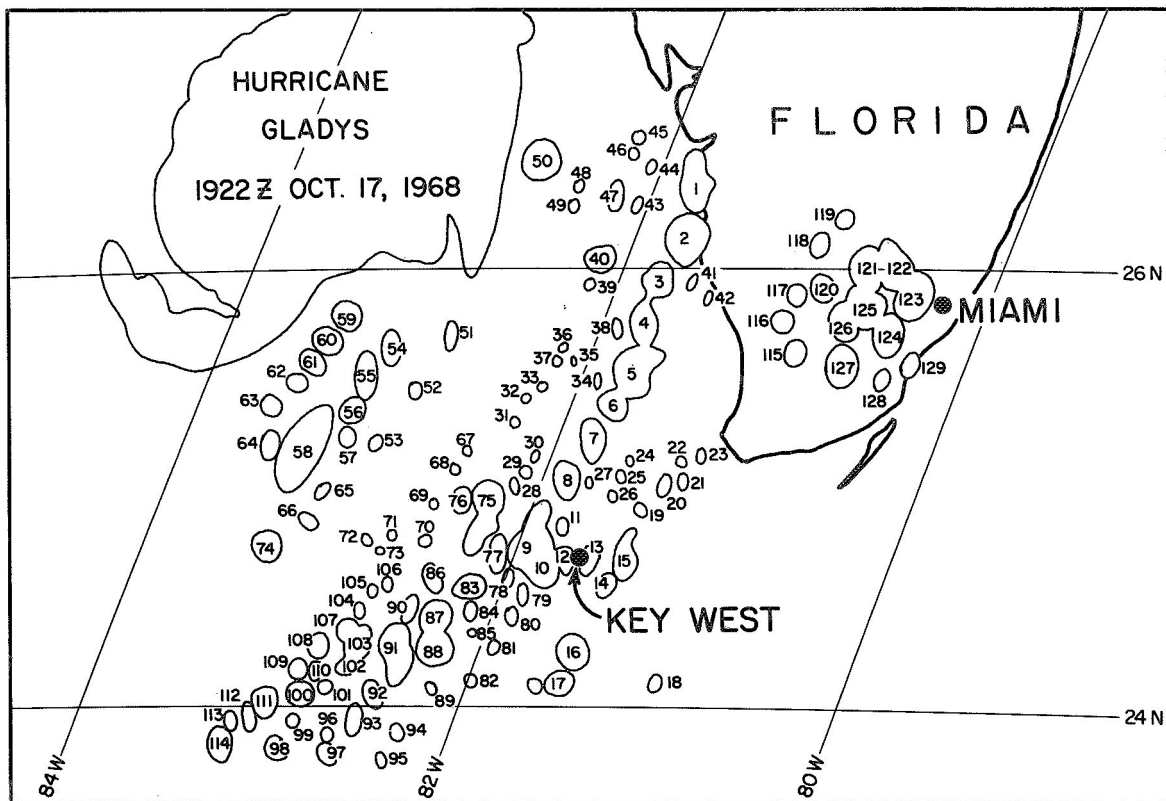


Fig. 4. Cellular clouds identified in Fig. 2 and numbered consecutively 1 through 129 for their life estimate.

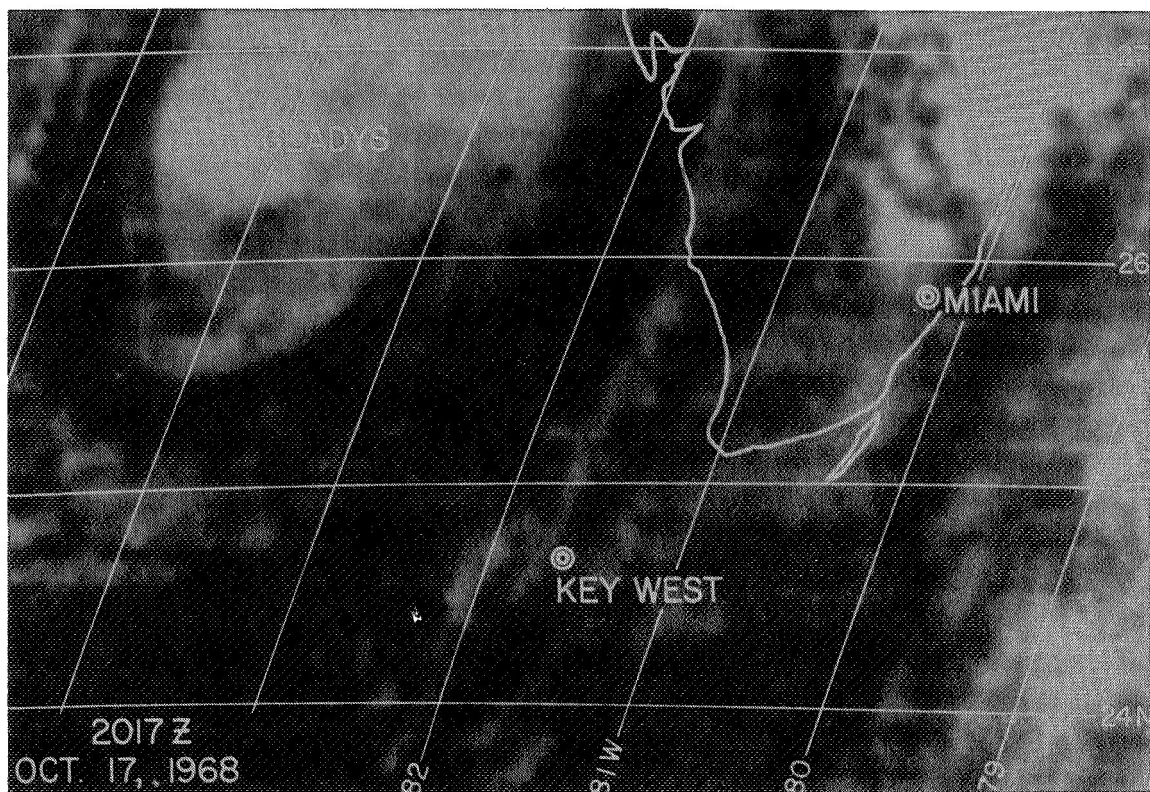


Fig. 5. An ATS III picture taken at 2017 GMT 50 minutes after the initial picture.

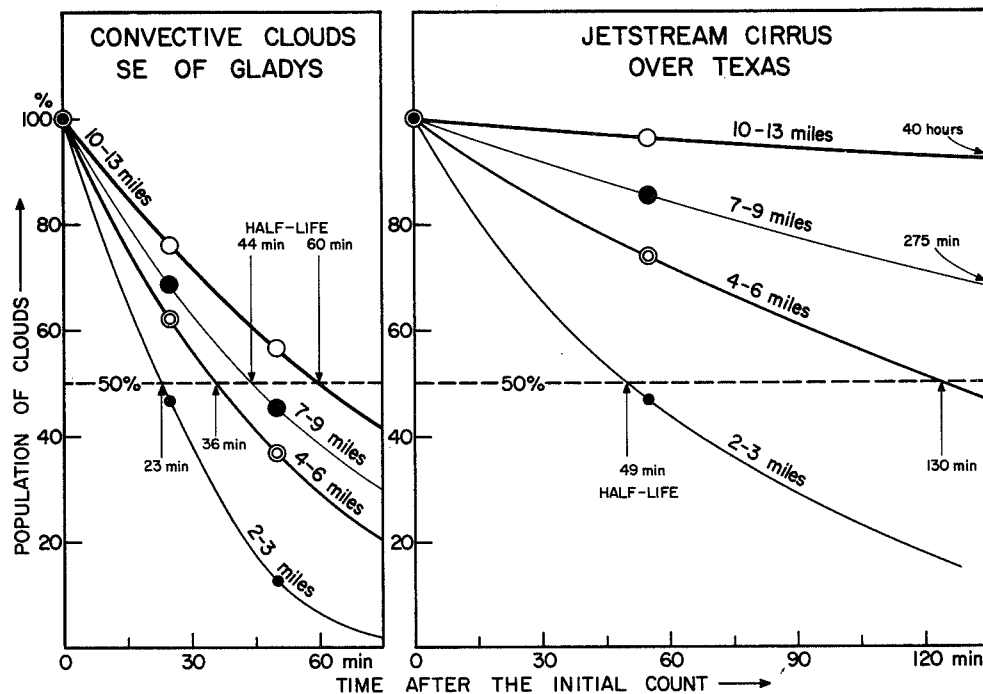


Fig. 6. Change in the population of clouds. Left: cumulus clouds in the southeast sector of Hurricane Gladys (see Figs. 2 and 5). Right: cirrus clouds over Texas (see Figs. 10 and 11). Note that the life of cirrus is several times longer than that of cumuli.

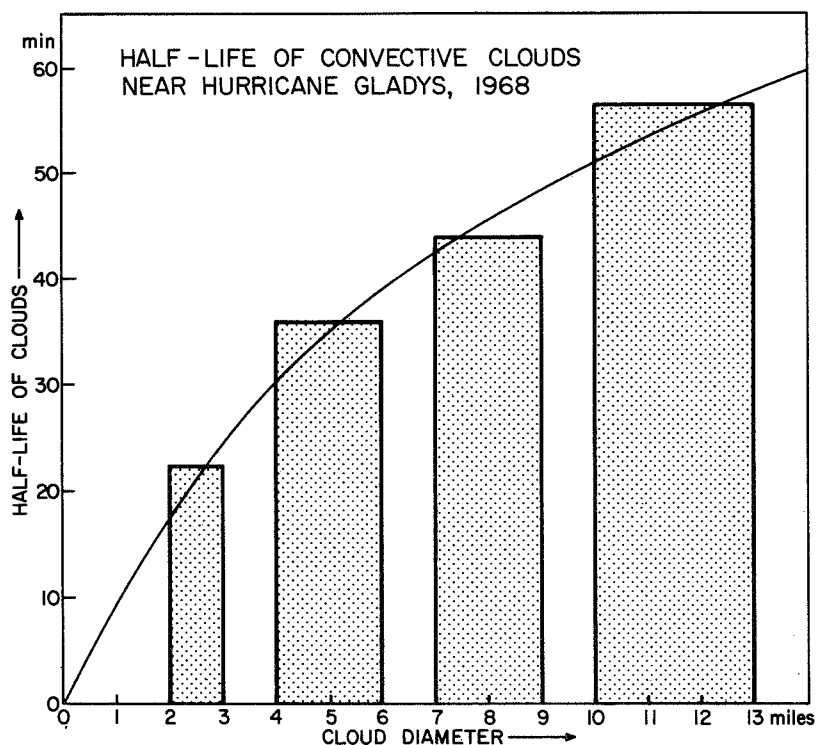


Fig. 7. Half-life of convective clouds plotted as a function of cloud diameter.

3. Cirrus as Tracers

While small convective clouds are used to estimate relatively low-level flow, cirrus clouds can be used for the determination of the location and fine structure of jetstreams.

A typical but rather complicated pattern of jetstream cirrus is shown in an Apollo picture (see Fig. 8) taken over the Rio Grande on March 9, 1969. Two cities, Laredo and Del Rio, Texas, are entered in the picture along with longitudes and latitudes at one-degree intervals. At these latitudes the distance between longitudes is about 50 nautical miles while that between latitudes is 60 nautical miles. The resolution of the picture is estimated to be about 1/10 mile, thus enabling us to determine the cloud types. Most of the clouds in the picture are cirriform with cellular configurations of various dimensions. For identification purposes, centers of cells with overall dimensions over 10 miles were indicated by letters A through S. Much smaller cirrus elements with 3 to 6 miles horizontal dimensions are indicated by small dots placed at each cloud center.

To determine the resolution of an ATS III picture a digitized ATS picture was enlarged and gridded in Fig. 9. Cells with identifications A through S correspond to those identified in Fig. 8. All cirrus elements larger than about 5 miles are clearly identified in the ATS picture, thus proving that the ATS III resolution is high enough for tracing small cirrus elements. Note that nine cirrus elements with a dot at each center are seen also in the ATS III picture.

Even small pieces of cirrus in a jetstream have a relatively long half-life, several times that of a cumulus half-life, of comparable dimensions. Two pictures in Figs. 10 and 11 were taken at 2014 and 2104 GMT March 9, 1969, 50 minutes apart.

During this time cirrus moved through a considerable distance while maintaining their configurations in the initial picture. To evaluate the half-life of these cirrus clouds, a total of 437 cirrus elements were identified in Fig. 10. Then their identity and survival in Fig. 11, a picture taken 50 minutes later, were studied carefully. The result is shown in Table I below.

TABLE I

Cloud size in n. m.	2-3	4-6	7-9	10-13
Initial count in Fig. 10	103.00	225.00	80.00	29.00
Count in Fig. 11	49.00	167.00	69.00	28.00
Fractional survival in 50 min	0.47	0.74	0.86	0.96
Half-life in min	49.00	130.00	275.00	2400.00

From the displacement of clouds between ATS III pictures in Figs. 10 and 11, cloud velocities were computed. To our surprise, computed speeds turned out to be the highest that have ever been computed from ATS pictures (see Fig. 12). The highest value was obtained near Abilene, Texas. It was 181 kt. The speed showed a gradual decrease toward the south, showing 120 kt near the south edge of the chart.

For detailed examination, fifteen clouds were selected within the diamond-shaped area in Fig. 10. This is the same area of an Apollo-9 picture taken almost simultaneously (see Fig. 13). The velocities of these clouds were entered in the Apollo picture with the city of Houston near the upper left and Galveston near the center. By looking at an Apollo picture such as this, one would not be able to imagine that these clouds were passing over these cities at 150 kt, because a still picture would not give us an idea of a cloud motion. Moreover, the velocity assigned to each cloud in Fig. 13 permits us to compute a large anticyclonic shear, 15 kt in 50 n. m. which is comparable to a relative vorticity of

$$\zeta \cong 8 \times 10^{-5} \text{ sec}^{-1}$$

The coriolis parameter at 30°N is $f = 7.3 \times 10^{-5} \text{ sec}^{-1}$ which is comparable to the relative vorticity of the cirrus velocity field. If cirrus elements are assumed to

move with the ambient air, the absolute vorticity of the flow is given by

$$Q = \zeta + f = \text{Zero}.$$

To determine the levels of air flow corresponding to such a high-speed cloud motion, vertical profiles of winds from Del Rio (DRT), Brownsville (BRO), Abilene (ABI), and Victoria (VCT) were plotted in Fig. 14. The mean cloud motion over each station is also shown in the figure. With the exception over BRO, cirrus speeds represent more or less the flow of 300-mb winds. Over BRO, however, the cirrus velocity corresponds to the 450-mb wind. While the moist layer was shown to be between the 400 and 450-mb layers. This would imply that the height of cirrus clouds sloped up toward the core of the jetstream.

We have shown a possibility of determining flow patterns within a jetstream by tracing cirrus elements, 3 to 10 miles in horizontal dimensions. These elements are spaced at certain intervals usually along the direction of the flow or the cloud motion. As long as we trace these elements manually, the picture intervals may not be a major concern as long as they do not exceed the approximate half-life of tracer clouds.

In order to develop an automatic system of tracing clouds through a pattern of recognition, it is desirable to keep taking pictures so that a cloud element would move less than one half of the cloud spacing, λ in Fig. 15. If a cloud moves as far as

λ during successive pictures, for instance, it would be difficult to look for a recognized pattern. On a movie, a cloud element might be standing still regardless of its translational motion. By limiting the picture interval, Δt to satisfy

$$V \Delta t < \frac{\lambda}{2}$$

where V denotes the cloud motion, we obtain

$$\Delta t < \frac{1}{2} \frac{\lambda}{V}$$

Lines of constant Δt on λ, V coordinates are straight lines converging at the origin. Figure 15 presents a group of these lines labeled with $\Delta t = 2, 4, 6, 8, 10, 20, 30$, and 40 min. It is evident that the picture interval is inversely proportional to the cloud speed. When cloud distance is 20 n. m. which is a commonly observed case,

a 6-min picture interval is required for clouds moving at 100 kt. The interval should be reduced to 3 min if a cloud moves at 200 kt.

RECOMMENDED FUTURE RESEARCH

(a) Further Study of the Life of Tracer Cirrus.

Cirrus clouds seem to survive much longer than convective clouds with comparable diameters. Their study as tracers is of great value to locate a jetstream and determine its local structure.

(b) Study of Cirrus Motion in Relation to Three-Dimensional Wind, Temperature, and Humidity Distribution within Jetstreams.

(c) The Exploration of the Possibilities of Taking ATS III Local Pictures at Five-Minute Intervals.

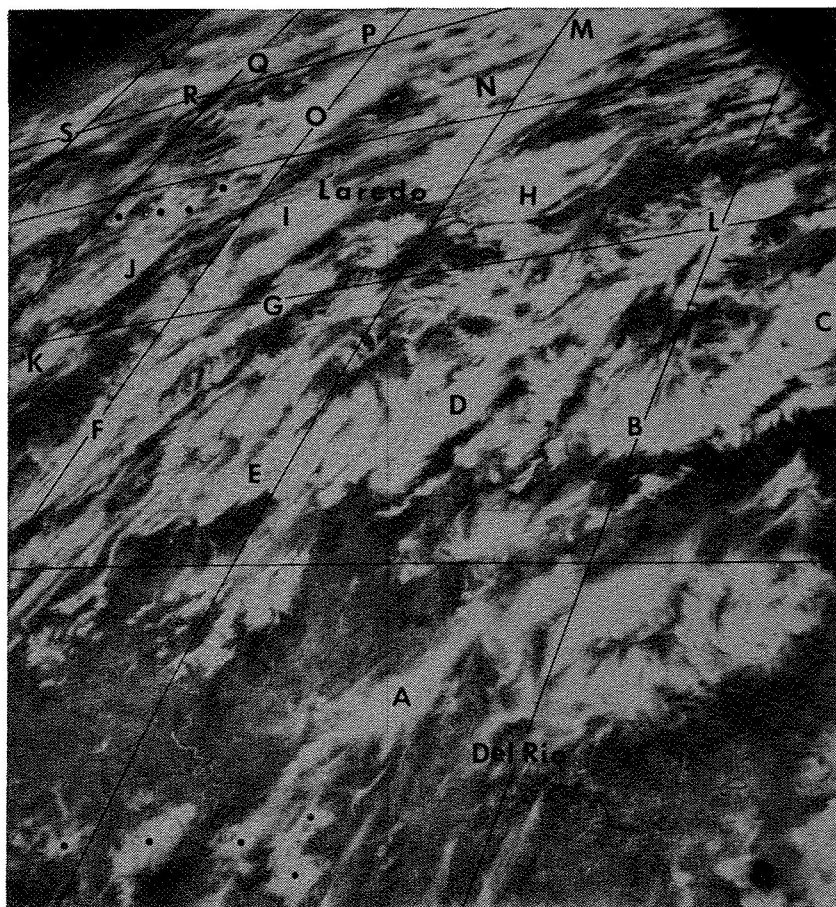


Fig. 8. Apollo 9 view of jetstream cirrus over the Rio Grande Valley showing their cellular structure. Selected cloud elements are identified by letters A through S.

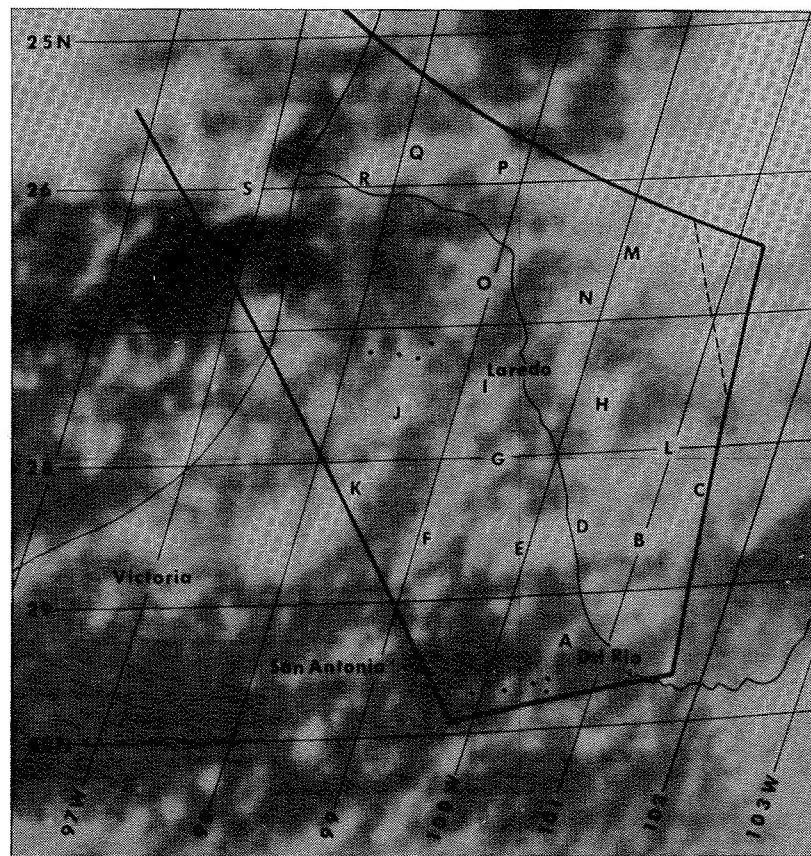


Fig. 9. An enlargement of an ATS III picture with the picture start time at 2014 GMT, March 9, 1969. Letters A through S designate the cirrus elements seen in the Apollo 9 picture in Fig. 8. It is amazing to find that each of the cirrus cells in the Apollo picture can be identified in this ATS picture as long as the cell size is larger than 3 miles.

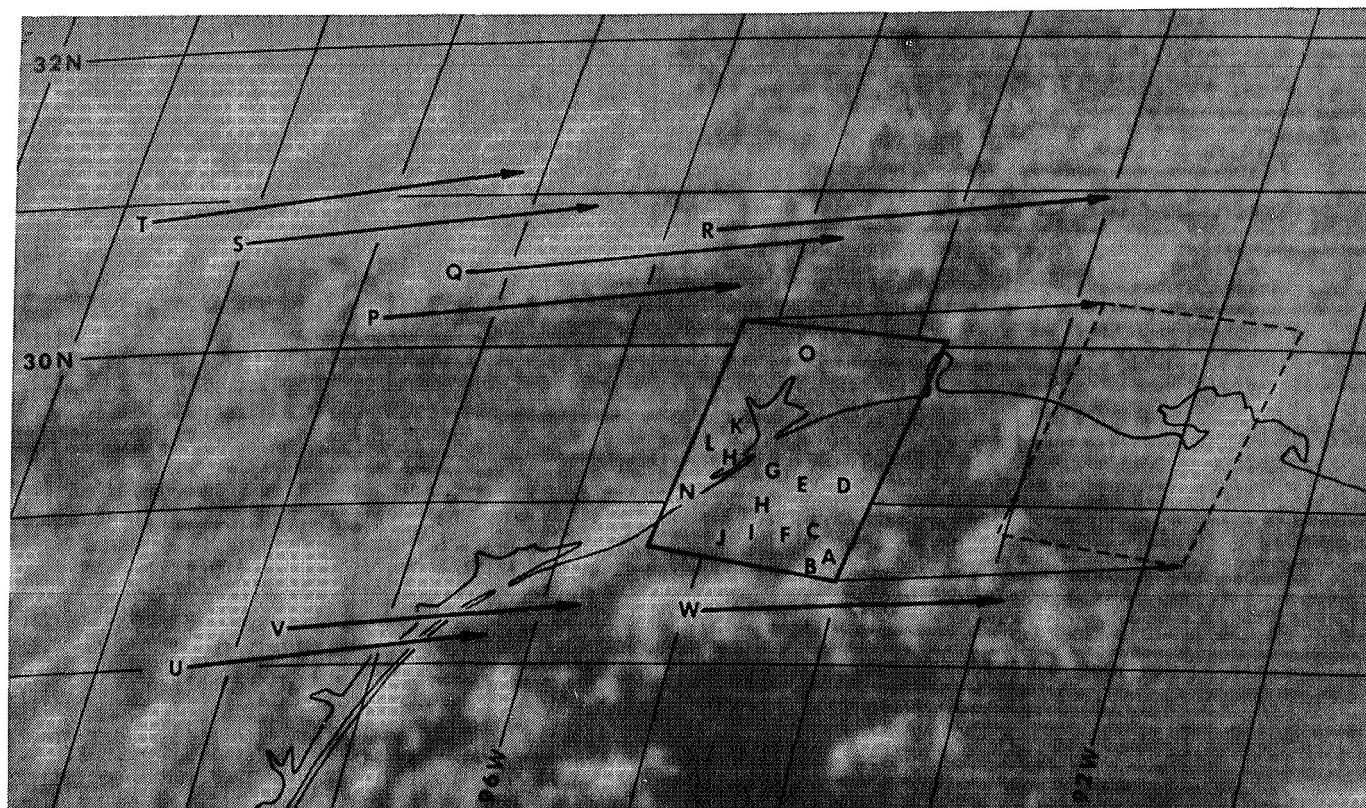


Fig. 10. An ATS III picture started at 2014 GMT March 9, 1969. Displacement of selected cirrus clouds and an area near Houston, Texas is shown by arrows.

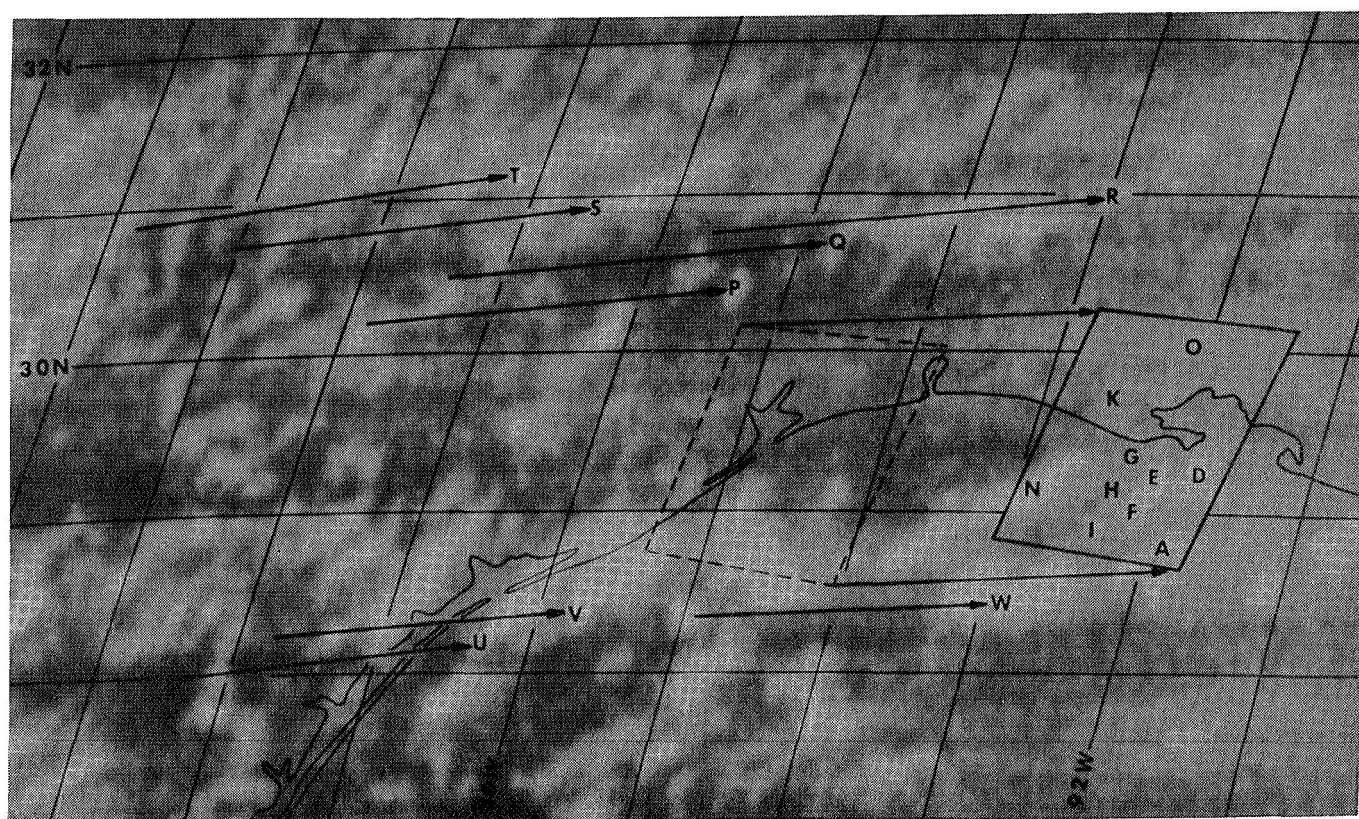


Fig. 11. An ATS III picture started at 2104 GMT March 9, 1969, 50 minutes after the picture in Fig. 10. A total number of 437 cirrus cells identified in Fig. 10 were examined in this figure to determine how many of them survived through this 50 minute period. The result is presented in Fig. 6.

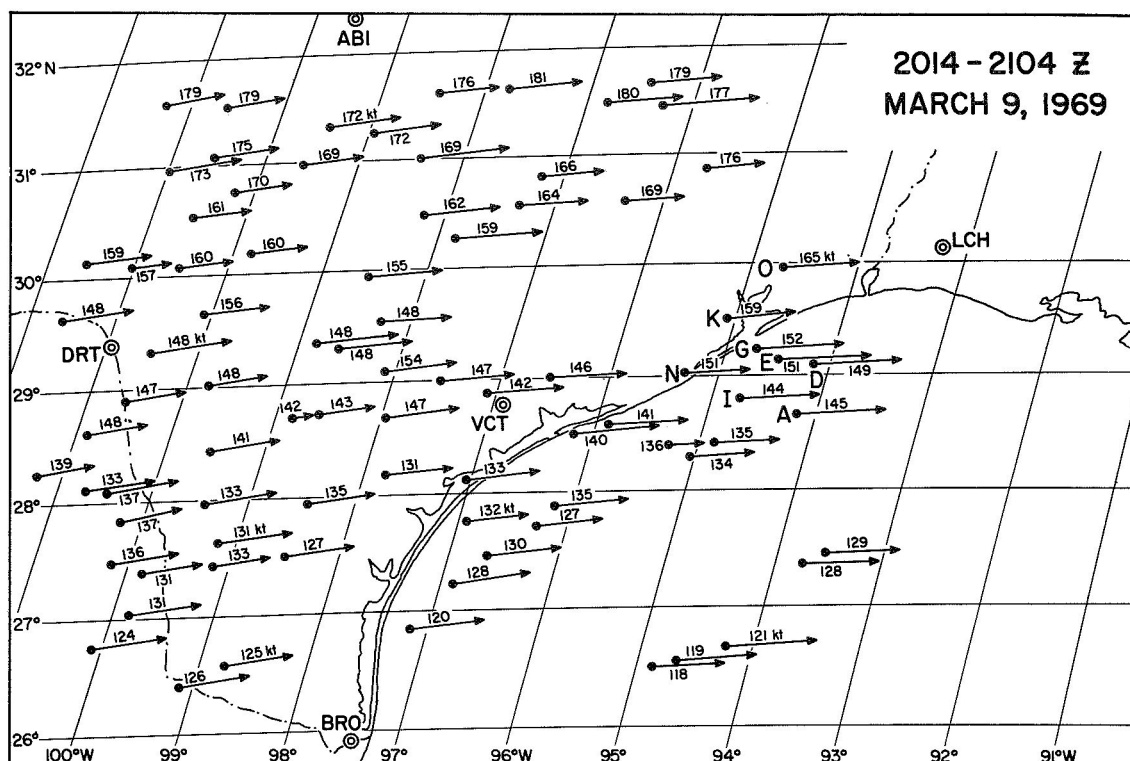


Fig. 12. Velocity of cirrus clouds computed from Figs. 10 and 11. Note that the fastest speed of 181 kt was measured near Abilene, Texas.

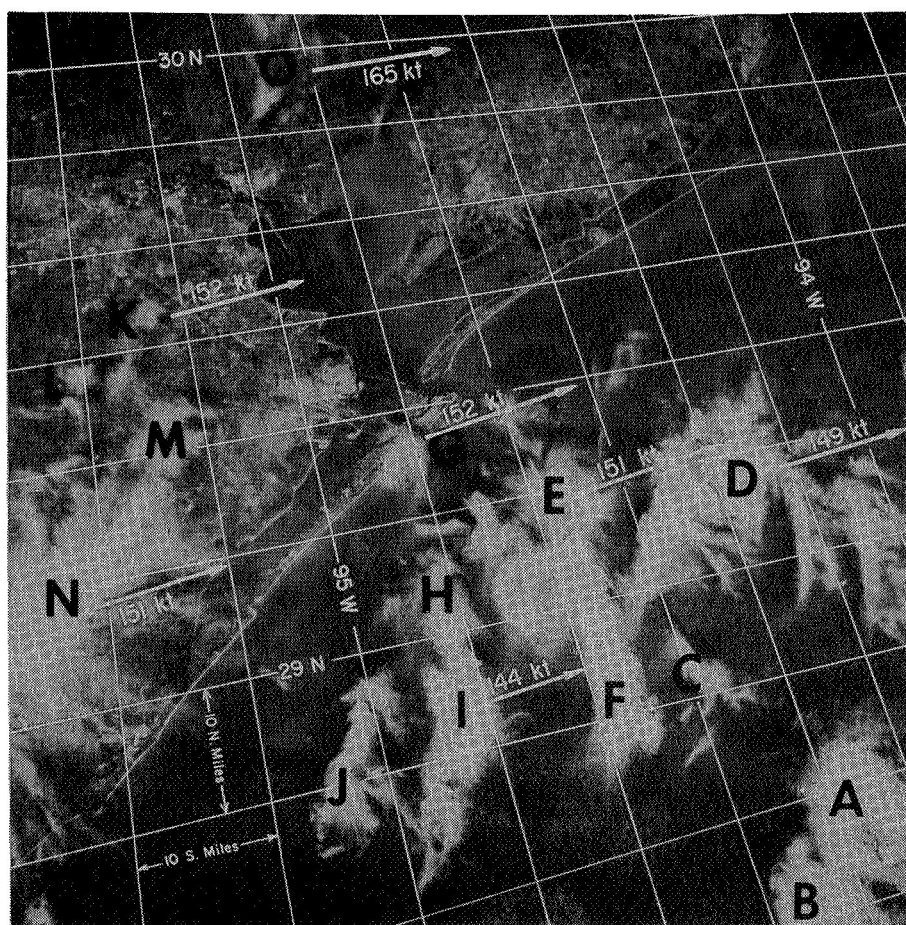


Fig. 13. Motion of cirrus clouds in an Apollo picture taken over Houston-Galveston area. Velocities were measured from ATS III pictures in Figs. 10 and 11. Refer to Fig. 12 for cloud identification.

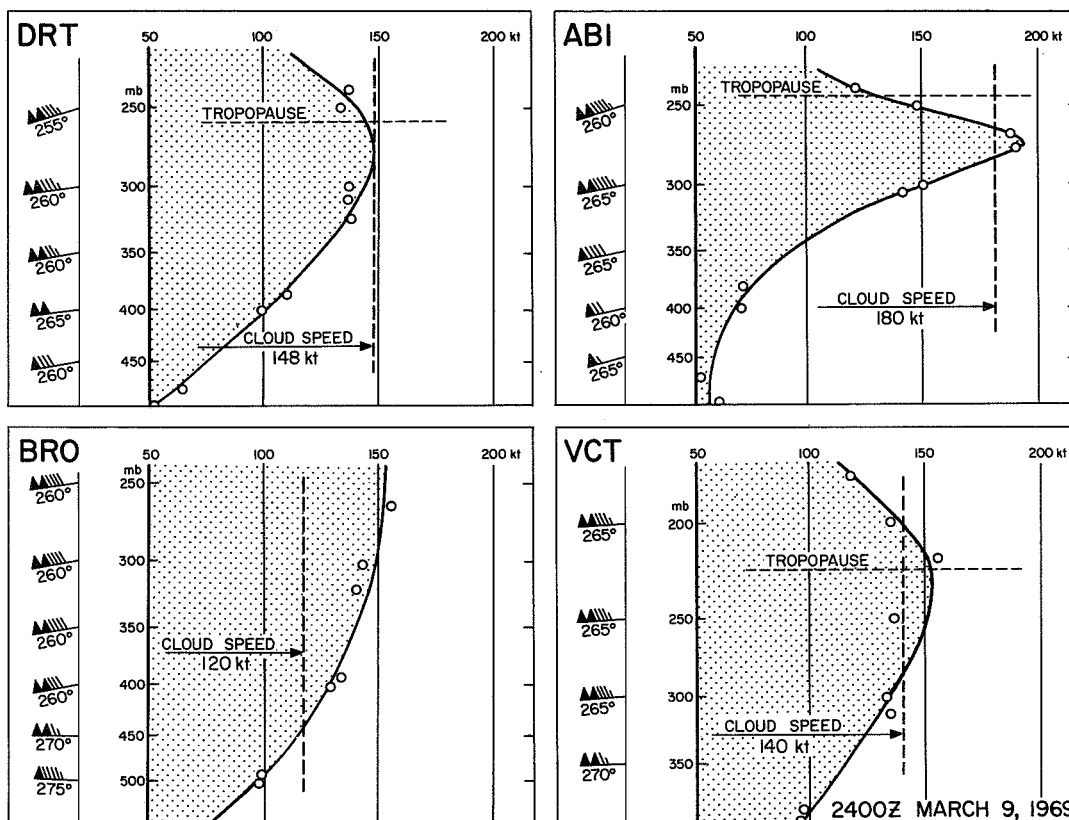


Fig. 14. Vertical wind profile obtained at 2400 GMT, March 9, 1969, from four upper-air stations in Fig. 12. The cloud velocity corresponds to 450 mb wind over Brownsville. North of Victoria, however, cirrus motion corresponds to 300-mb wind.

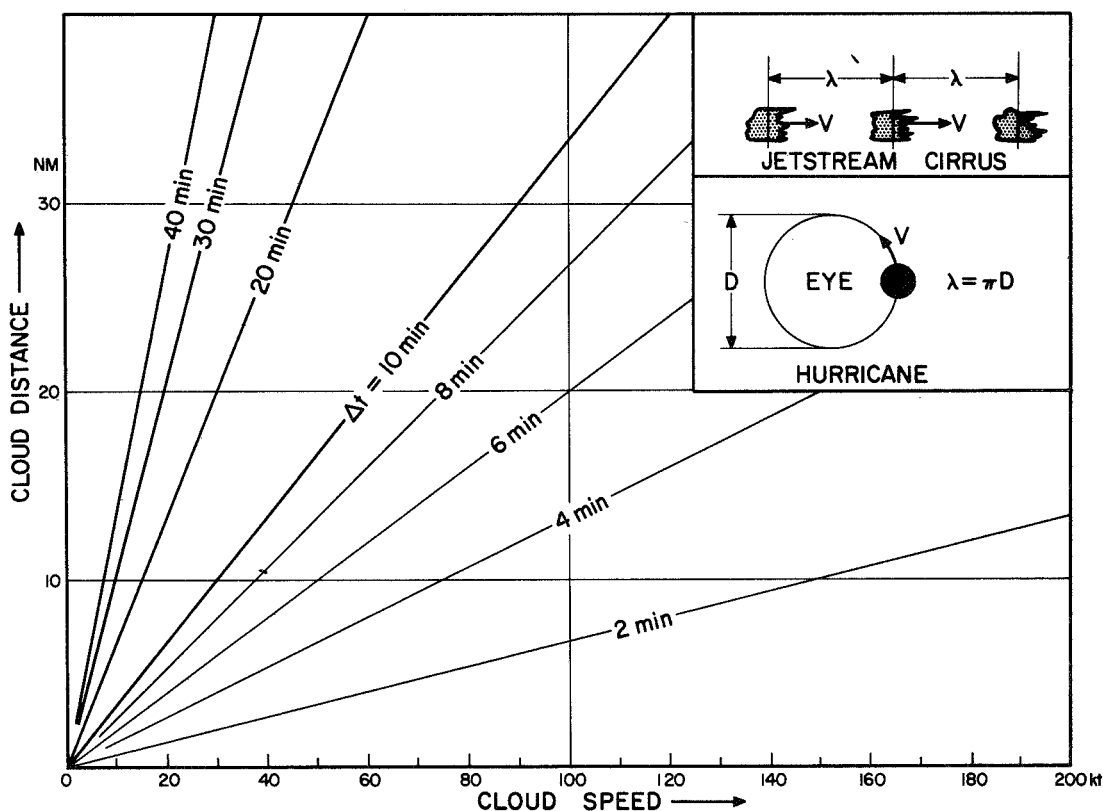


Fig. 15. Picture interval or frame time required not to move cloud element beyond one half of the cloud distance. For a convective tower in a hurricane eye wall, the cloud distance may be regarded as the circumference of the eye.

4. Detection of Overshooting Cloud Tops

For the detection and short-range forecast of severe storms including intense hurricanes such as Camille, it would be necessary first to determine the environmental flow around a storm and then to pinpoint the portion of severe activities.

A typical cumulonimbus cloud over the Midwest is presented in Fig. 16. The picture was taken near Salina, Kansas, looking toward the southeast more or less perpendicular to the flow indicated to the right of the cloud. Schematic stream lines in the vertical plane through the cloud center are superimposed upon the cloud picture. The tropopause which was not very well-defined in temperature soundings was at about 11 km while the overshooting top reached to 13.2 km. Such an overshooting of about 2 km is rather common among severe storm-producing thunderstorms. Horizontal dimensions of overshooting tops vary from storm to storm but they are normally only a few percent of the cirrus area surrounding these tops.

An Apollo picture showing a vertical view of a moderate thunderstorm over Colombia, South America, appears in Fig. 17. Horizontal scales in nautical miles and milliradians are given at the bottom. Scan spots defined by milliradians of a half-power diameter viewed from the geosynchronous altitude are given at the top so as to compare them with the cloud patterns to be detected. The local time of the picture (about 5 hours less than 2146 GMT), 1645 LST would result in a 30° elevation angle of the sun shining upon the overshooting top. A 4-mile cloud shadow length would be produced by a 2.3 n.m. or a 4.3 km overshooting above the general height of the cirrus surrounding the top. The diameter of the overshooting top is measured to be about 3.5 n.m. or about 0.15 to 0.20 milliradians.

Unless the solar elevation angle is less than 45° the reflectance of the overshooting tops is a few percent higher than that of surrounding cirrus areas. It is, therefore, feasible to enhance the brightness of overshooting cloud tops. An example of an enhanced ATS III picture is presented in Fig. 18. The picture shows Hurricane Camille on Aug. 18, 1969 when the storm center was approaching the Mississippi Delta. One-degree lines of longitude and latitude are superimposed upon the picture. The

enhanced pattern of clouds near the hurricane center suggests a double-eye structure which is seen occasionally in well-developed hurricanes.

The best way of learning the correspondence between enhanced brightness and overshooting tops is to superimpose radar echo patterns into the ATS picture. Thus, the composite radar echoes from three WSR-57 radars were distorted to fit the projection of Fig. 18 and superimposed upon an unenhanced picture in Fig. 19. It is seen that the satellite picture over the hurricane is rather flat outside the region of radar echoes. These echoes and enhanced cloud patterns show a remarkable correspondence. This may mean that a 2 to 4 mile resolution of ATS III's visible picture is good enough for storm detection purposes if we improve our capability of brightness enhancement.

RECOMMENDED FURTHER RESEARCH

- (a) The Enhancement of Hurricane, Tornado, Snow Storm, and Other Pictures to Find Out the Correspondence between Enhanced Clouds and Overshooting Tops.
- (b) Further Analyses of Apollo 9 Pictures Together with Enhanced ATS Pictures.
- (c) Research on Tornado-producing Clouds.
- (d) The Estimation of Hurricane Wind Speeds from the Motion of Enhanced Cloud Cells.
- (e) Detection of Heavy Snow Areas in Relation to Cloud Brightness.

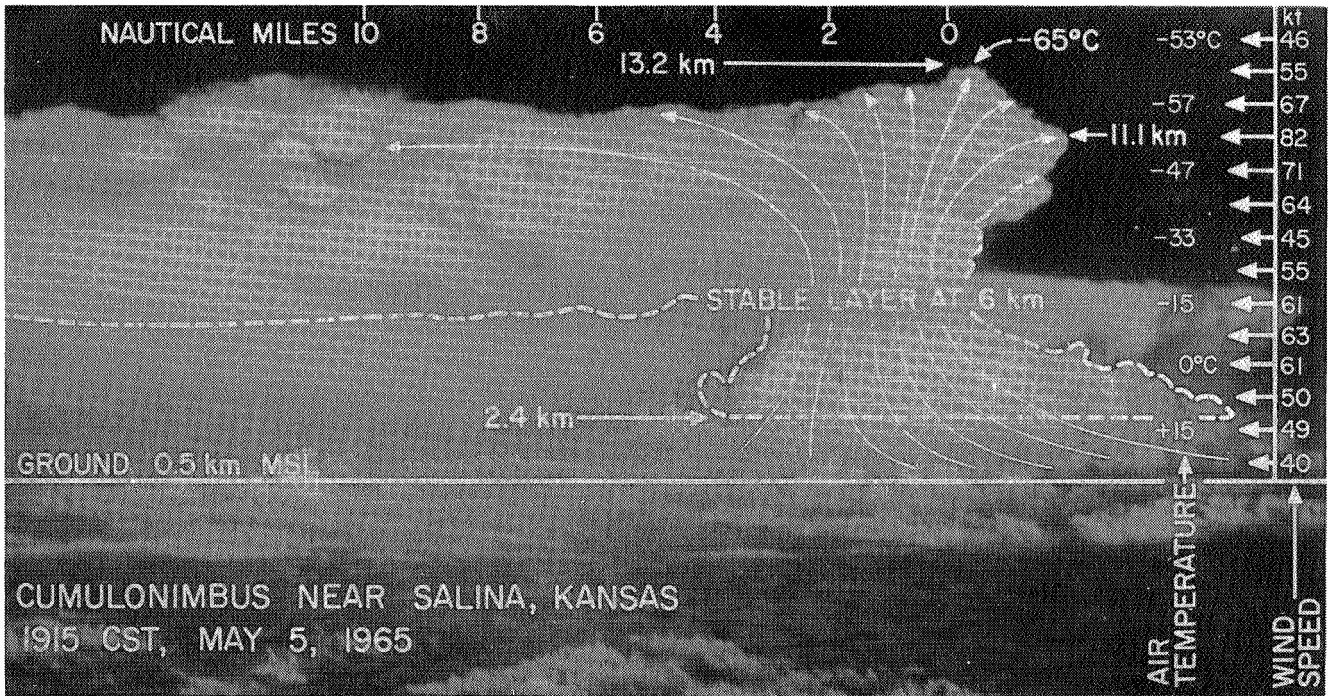


Fig. 16. Schematic vertical cross section of a cumulonimbus near Salina, Kansas. This picture was taken by the author on board ESSA's DC-6 during the 1965 tornado-research mission. The cloud was located 30 miles from the aircraft flying at 6-km altitude.

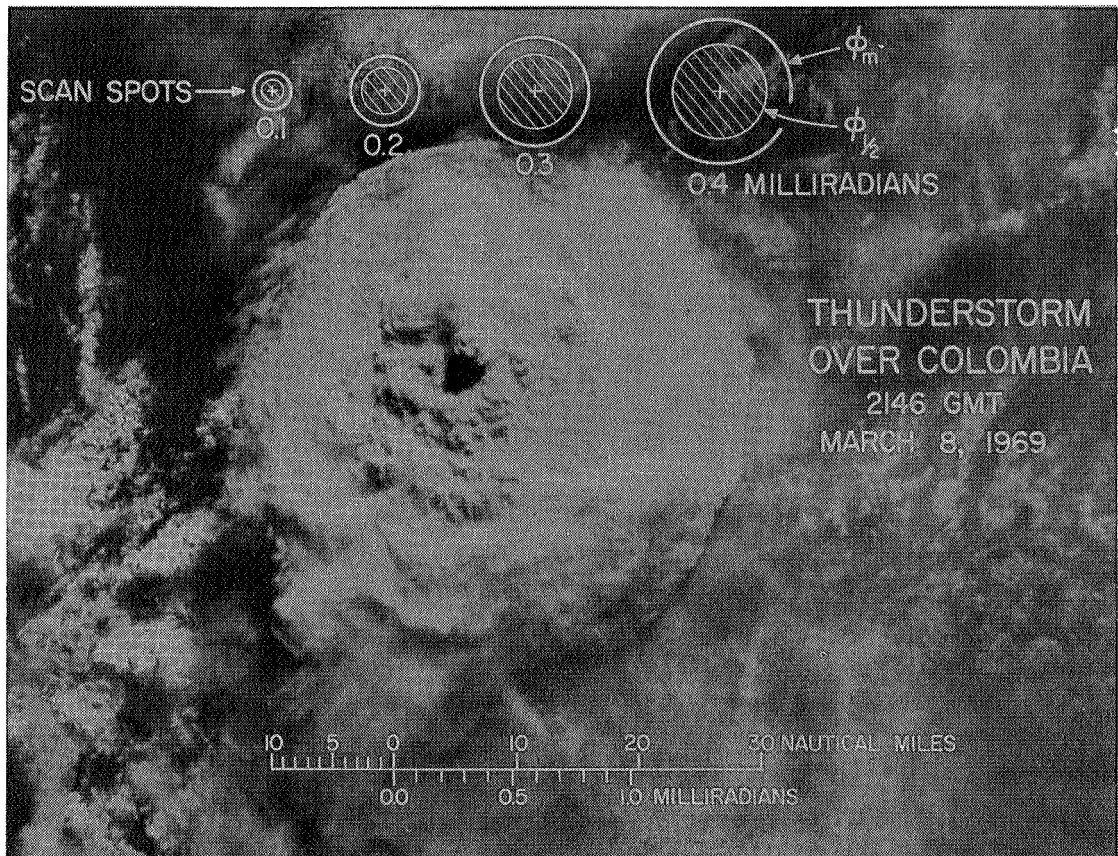


Fig. 17. An Apollo 9 view of an overshooting top. The circular shape of the anvil results partly from the lack of Coriolis force near the equator.

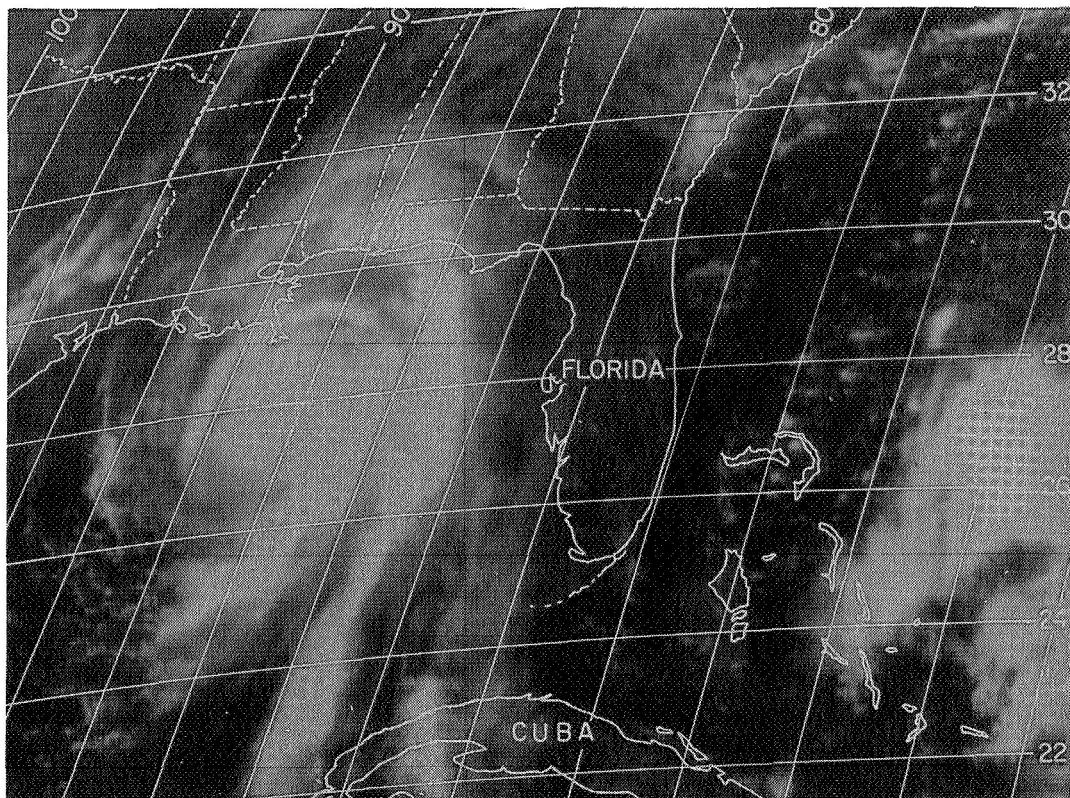


Fig. 18. Enhanced picture of Camille with one-degree geographic grids superimposed. Picture start time: 172333 GMT August 17, 1969.

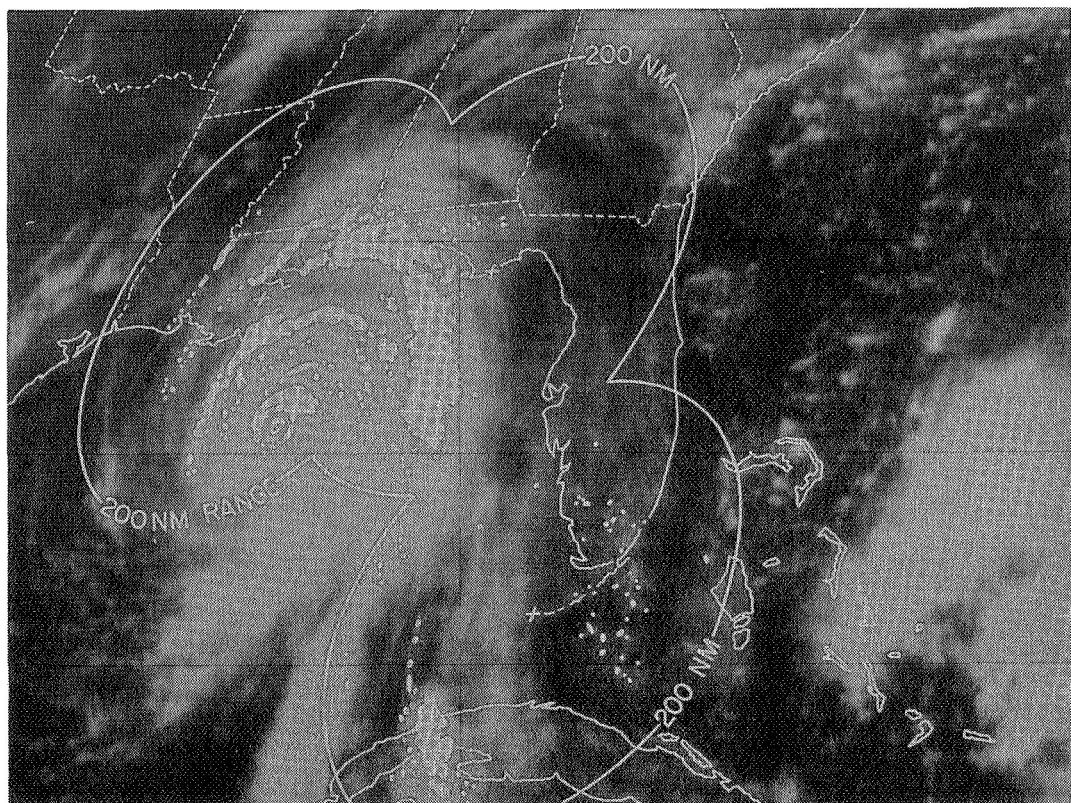


Fig. 19. Unenhanced Camille picture with superimposed radar echoes from Key West, Apalachicola, and New Orleans. Radar pictures were taken within a few minutes of the ATS scan time.

5. Resolution of Spin Scan Radiometers

It is our desire to detect clouds for their uses in diagnostic and subsequent prognostic purposes. Requirements vary according to the objectives. We have to live with a finite spacial resolution of spin scan radiometers, the response of which decreases from the center outward until it reaches zero.

Figure 20 was constructed from the Nimbus III User's Guide showing the angular field of view of the 10 to 11 micron channel. The spacial response of future spin scan radiometers may not be characterized by that of Nimbus III, but we may approximate the response with reasonable accuracy. The diameter of the maximum field of view is indicated by ϕ_m while $\phi_{1/2}$ denotes the diameter of the half-power scan diameter.

To show a smoothing effect coming from a finite field of view of the scan spot size, two cloud bands of one-mile width were scanned through a computer simulation. As shown in Fig. 21, the half-power field of view or IFOV was kept at 1.7 miles with the maximum field of view, $\phi_m = 2.5$ miles. The reflectance of the bands was assumed to be 100%. When two bands are placed side by side without leaving a space between bands, a cloud band of a 2-mile width will be scanned. At the central position of the scan, IFOV is located completely inside the band, but the maximum field of view extends beyond the edge of the band, resulting in a 98.7% reflectance of the cloud band. By separating the band by a quarter of a mile, we still get the maximum reflectance of 82.0% when the radiometer axis points to the cloud-free space between the bands. Until the bands are separated by approximately 1/2 mile, measured reflectance fails to show two maxima corresponding to each band. A much wider spacing of the bands reduces the reflectance to 68% due to partial filling of the radiometer's field of view while showing the clear separation of these bands.

To determine design criteria of the spin scan infrared radiometers a simulated scan experiment was performed. The spacial response curve of Fig. 20 was adopted by varying ϕ_m or $\phi_{1/2}$ into certain discrete values. It is also necessary to establish certain model clouds in order to reduce evaluation parameters. In view of the importance of severe storm detection, a model cloud was chosen as an overshooting cloud top which would be the most difficult cloud type to be detected by a radiometer,

because its effective radiance is very small while surrounded by a cold cirrus shield. If we design a system of detecting such an overshooting model cloud it would detect other clouds without any difficulty.

A hard-to-detect model cloud was defined to be of a circular shape in a plane position with a variable diameter, D . The vertical cross section through the cloud center is an ellipse with cloud-top temperature of $-72^{\circ}\text{C} = 201^{\circ}\text{K}$. The environmental cirrus was assumed to be $-60^{\circ}\text{C} = 213^{\circ}\text{K}$ with 1.0 emissivity. A linear change in cloud-surface temperature with respect to the height was also assumed (see Fig. 22). The effective radiance at the bottom corresponds to that of Nimbus 3 HRIR Flight Unit F-5.

A computer simulation was made to determine the effective radiance defined by

$$\bar{\bar{N}} = \frac{\int \phi_{\omega} \bar{N}_{(\omega, T)} d\omega}{\int \phi_{\omega} d\omega} \quad (12)$$

where $\bar{N}$ denotes the effective radiance within the field of view with the spacial response ϕ_{ω} and $d\omega$, the solid angle element seen from the satellite. $\bar{\bar{N}}$ is the effective radiance detected by the radiometer. Due to the finite view of a radiometer, $\bar{N}$ and $\bar{\bar{N}}$ are different from each other unless $\bar{N}$ is constant within the entire field of view. Since $\bar{N}$ and $\bar{\bar{N}}$ correspond, respectively, to equivalent blackbody temperature $T_{\text{BB}}(\bar{N})$ and $T_{\text{BB}}(\bar{\bar{N}})$ we define the single-cloud $\Delta T(\text{SC} \Delta T)$ as

$$\text{SC} \Delta T = T_{\text{BB}}(\bar{N}) - T_{\text{BB}}(\bar{\bar{N}}) \quad (13)$$

when both T_{BB} represent the value at the center of a single cloud. In view of the fact that $\text{SC} \Delta T$ varies according to the partial filling of the field of view, it should vary only with the ratio, IFOV/D as long as the axis of a radiometer points toward the center of a model cloud.

Presented in Fig. 23 is the computer simulated $\text{SC} \Delta T$ obtained by changing IFOV/D between 0.33 and 5.33. When IFOV is zero, $\text{SC} \Delta T$ naturally shows the temperature difference, 12°C between the overshooting top and its environmental cirrus shield.

By increasing IFOV to as large as the model-cloud diameter, $SC\Delta T$ becomes 6°C , meaning that the measured cloud top temperature would be 6°C warmer.

For the purpose of detecting the existence of an isolated model cloud, however, it is not necessary to measure the correct cloud-top temperature. Instead, the temperature difference $SC\Delta T$ is required to be larger than the noise equivalent temperature field.

According to Alishouse, $NE\Delta T$ at 200°K and 100 rpm of spacecraft rotation varies according to the IFOV in milliradians as follows: 0.15 mr (12.83°C), 0.20 (4.80), 0.25 (2.47), 0.30 (1.50), and 0.50 mr (0.47°C). From these figures and his estimate of radiometric temperatures of isolated clouds, Yates concluded that a small cloud can be more readily detected with a large field of view than a small field of view. His conclusion is somewhat paradoxical but it is quite true.

To prove Yates' finding, Fig. 24 was drawn on IFOV vs. D coordinates. Isotherms radiating from the origin are those of $SC\Delta T$ read off from Fig. 23. Intersections of horizontal lines representing various IFOV in milliradians and corresponding $SC\Delta T$ separate the detectable cloud diameters from undetectable diameters. It is obvious that a larger field of view is suitable for the detection of a smaller model cloud. As shown by Yates' findings, an added radiance from the cloud environment suppresses the detection noise at a rate larger than the reduction of $SC\Delta T$ due to the increase of the field of view.

Detection of severe storms often involves separation of an overshooting top from nearby cloud tops. In such a case a radiometer must be capable of measuring a minimum value of N corresponding to each top. Simulations were made, therefore, by placing two model clouds at an edge-to-edge distance, S . Such a scan mode is illustrated in Fig. 25. The twin-cloud ΔT was thus defined as the difference in temperatures at the cloud center and at the midpoint of two clouds. This temperature difference is called the twin cloud ΔT ($TC\Delta T$). When the distance, S , is large, $TC\Delta T$ is always positive because a radiometer measures lower T_{BB} at each cloud center. For small S combined with large IFOV, $TC\Delta T$ becomes negative because, as in the case of two cloud bands in Fig. 21, a radiometer pointing toward the midpoint gives a colder temperature, since it is influenced significantly by both clouds. No separation

of two clouds is feasible when $TC\Delta T$ is negative.

Even with the positive values of $TC\Delta T$, two clouds can be separated only when

$$TC\Delta T > NE\Delta T.$$

A detectable domain satisfying the above condition is illustrated in Fig. 26 by placing two identical model clouds side by side. Four painted circles denote the limit of detectable diameters. It is of interest to see that 0.25 mr gives the smallest diameter of 5.5 miles, meaning that two clouds with larger diameter can be separated from each other. When IFOV is increased to 0.5 mr, the cloud diameter must be more than 9 miles in order to be detected as two clouds.

When the cloud top is 24°C colder than the environment, instead of 12°C , for instance, detectable domain can be estimated simply by relabeling $TC\Delta T$. Accepting a crude approximation we simply doubled the $TC\Delta T$ to determine the detectable domain for much colder cloud tops. For accurate estimation we have to start from the effective radiance which is not proportional to the absolute temperature. The result indicates that 0.20 mr gives the smallest diameter of 4.5 miles or larger for the detectable cloud diameter. A case of 6°C colder cloud was also obtained approximately as shown by the line labeled with -6°C . For detection of twin clouds, therefore, it may be stated that the detection capability depends upon various parameters such as cloud diameter, temperature, $NE\Delta T$, etc.

The final diagram in Fig. 27 was constructed by changing the twin cloud diameters from 3 to 8 nautical miles on IFOV vs. S coordinates. When IFOV is 0.50 mr, for example, twin clouds of 8-mile diameter can be detected as two clouds if their separation is 1.5 miles or larger. Twin clouds with 3-mile diameters must be separated by at least 9 miles before they can be seen as two clouds. By reducing IFOV to 0.20 mr, 4-mile clouds can be detected when they are more than 2-miles away. Two 3-mile clouds can never be detected no matter how far they are separated.

RECOMMENDED FUTURE RESEARCH

- (a) Investigation of Temperature Field of Overshooting Cloud Tops.
- (b) Simulation of Measured Temperature Fields of Single, Twin, and Multi-Clouds.
- (c) Simulation Experiment of Sea-Surface Temperature Gradient by Changing IFOV.
- (d) Determination of Proper Scan-Line Intervals for Depiction of Multiple Cells.

Fig. 20. Spatial response of Nimbus III HRIR radiometer used in simulating the measured radiance in this paper.

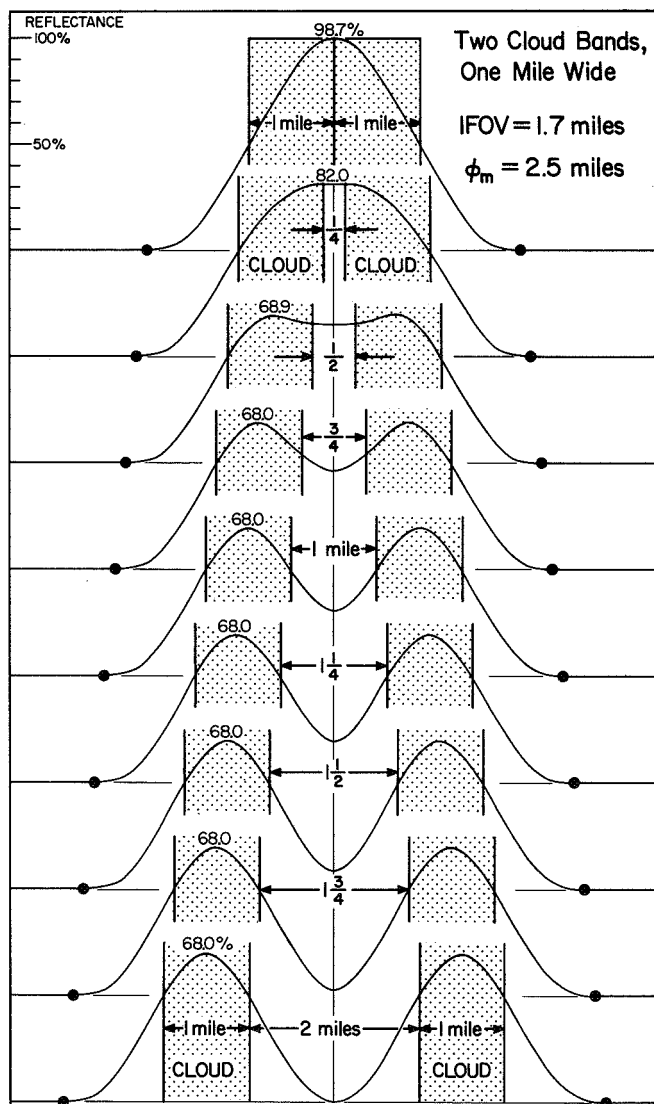
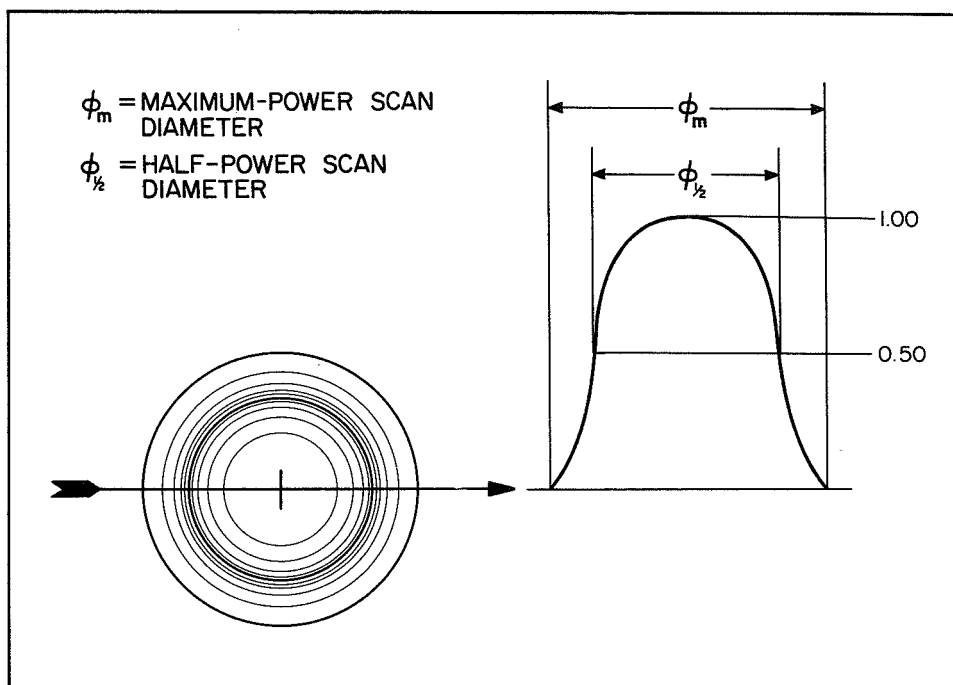


Fig. 21. Simulated results of reflectance change across two parallel cloud bands. A 100% reflectance was assigned to these bands.

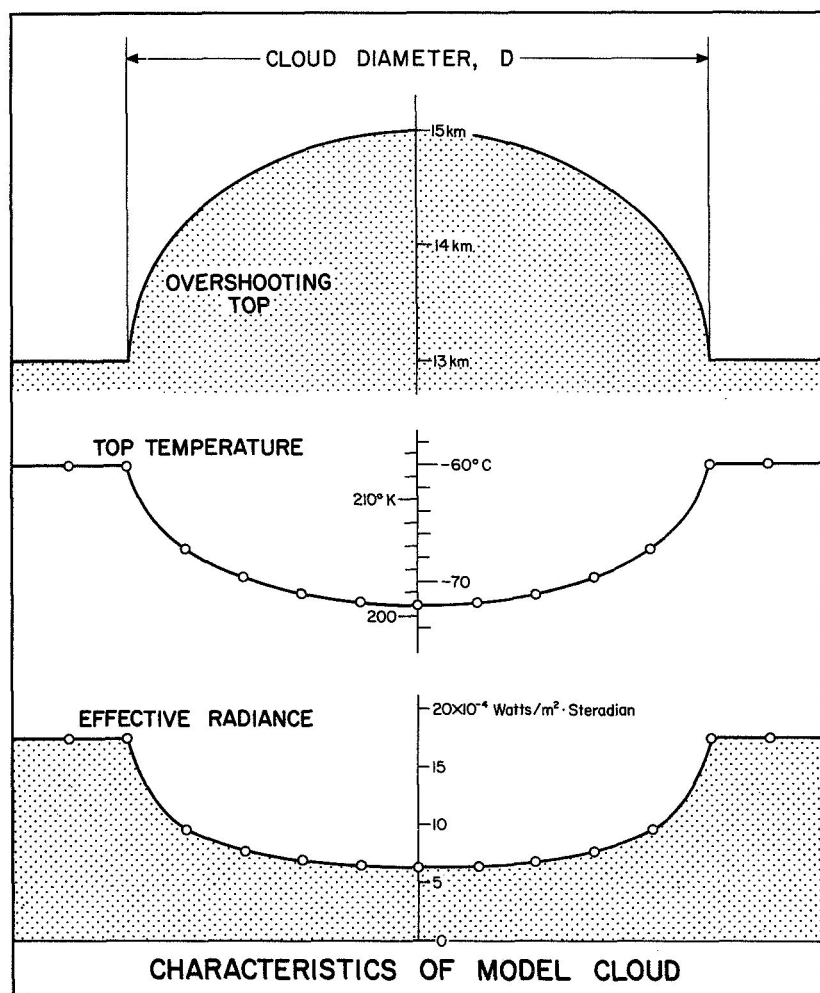
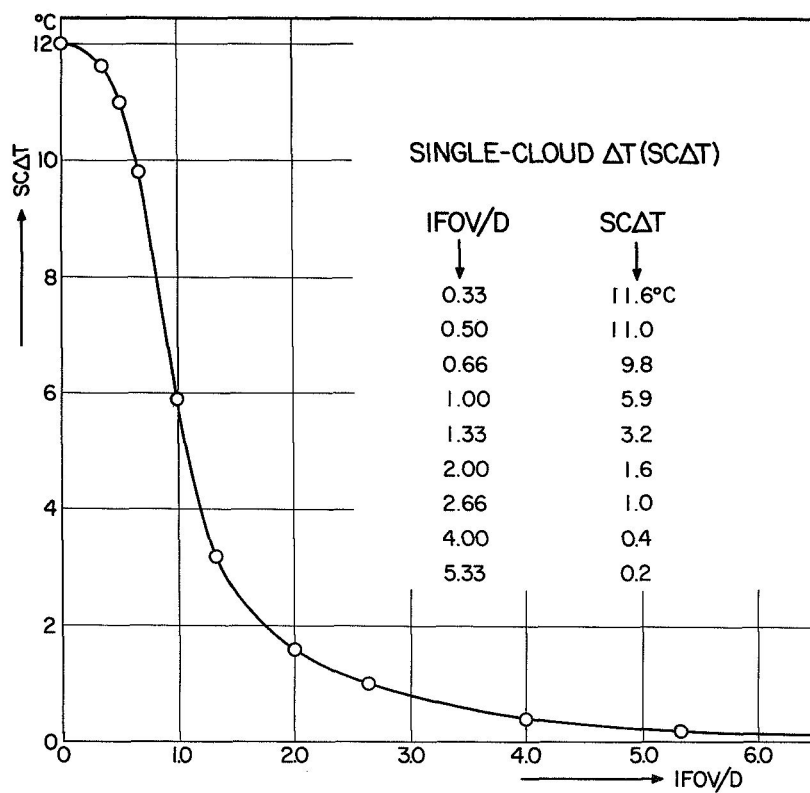


Fig. 22. Height, temperature, and effective radiance of a model cloud with variable diameters and a fixed overshooting height of 2 km. The lapse rate of the cloud surface temperature is assumed to be 6°C per km.

Fig. 23. Single-cloud ΔT , the temperature deficit to be measured by a radiometer as it scans through the center of the model cloud in Fig. 22.



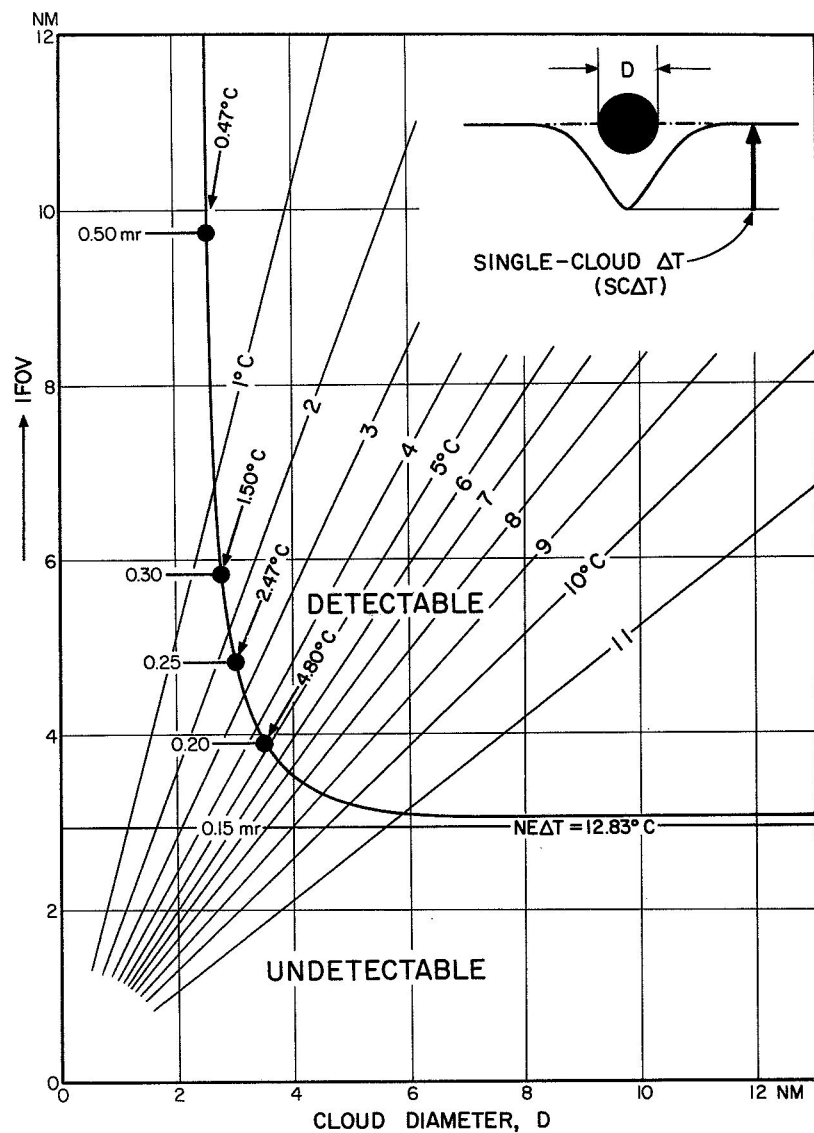


Fig. 24. Diagram to show the fact that the larger the field of view the smaller the diameter of detectable clouds. This fact was first pointed out by Yates in his letter to NESC Director dated Nov. 17, 1969.

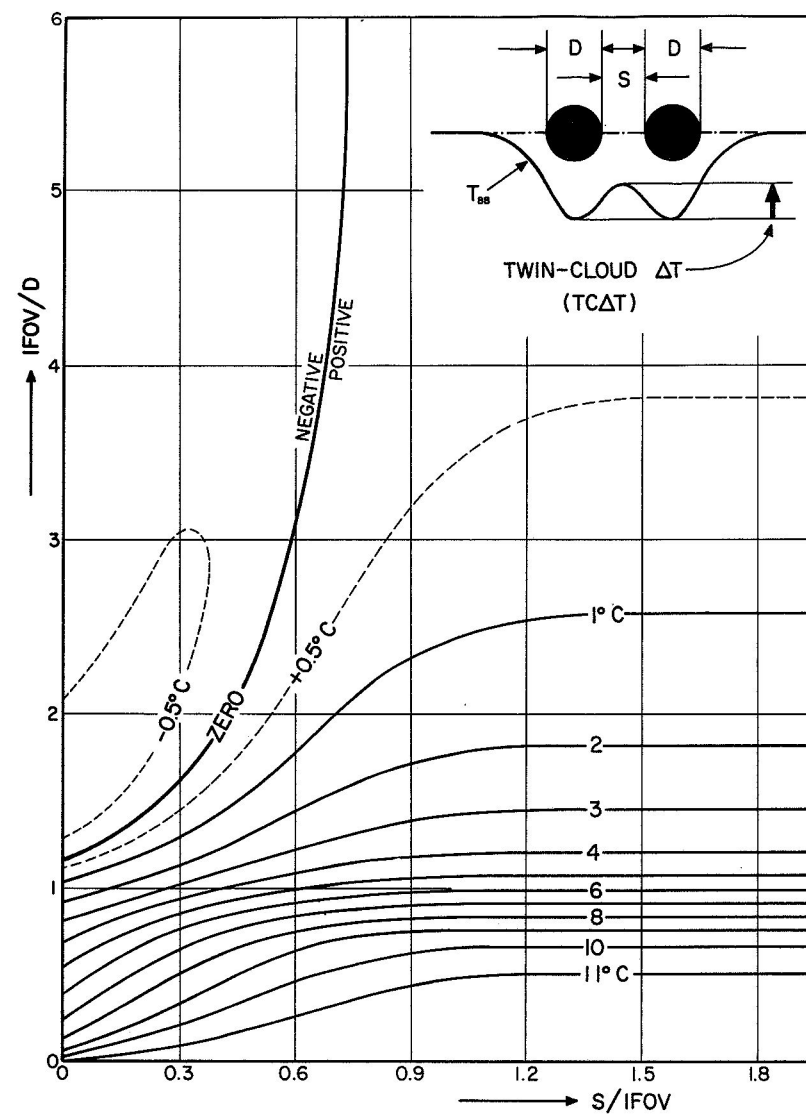


Fig. 25. Twin-cloud ΔT applicable to two clouds with diameter D , separated by S , in the direction of the scan.

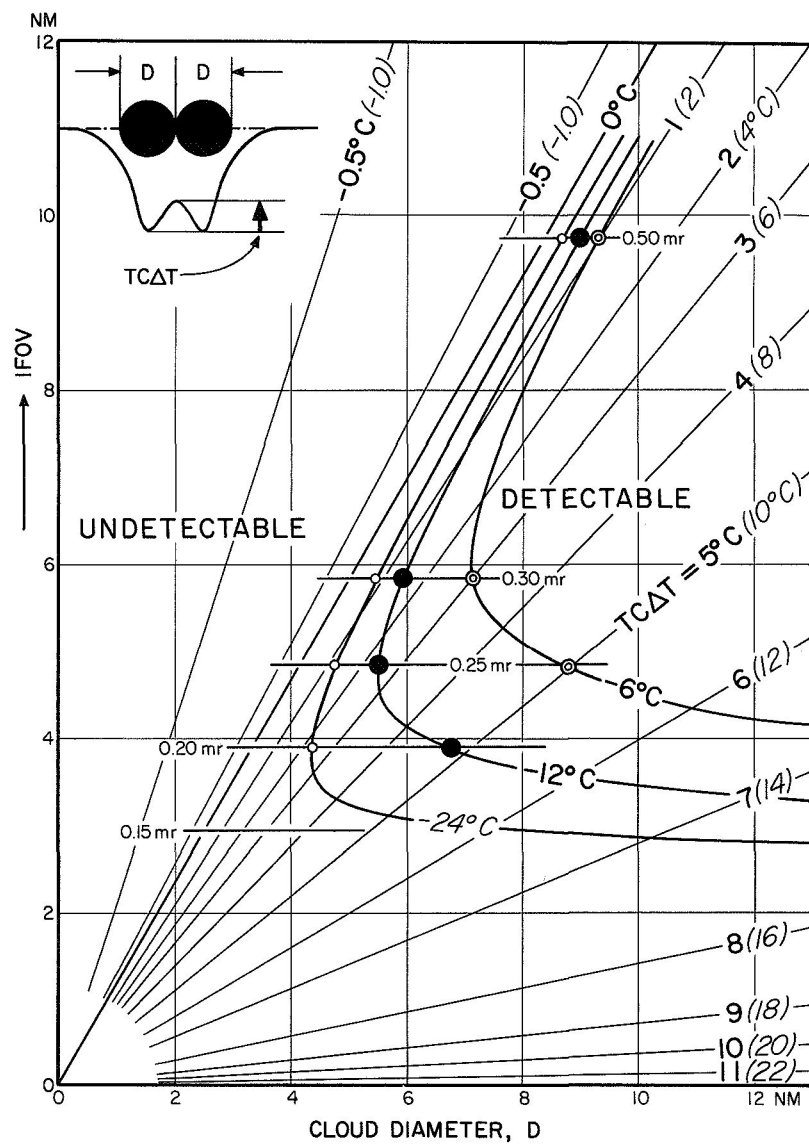


Fig. 26. Detectable diameter of twin clouds arranged in a contact position in the scan direction. An exact simulation was performed for the model cloud with 12°C colder cloud top. Cases of 6°C and 24°C were obtained through an approximate method.

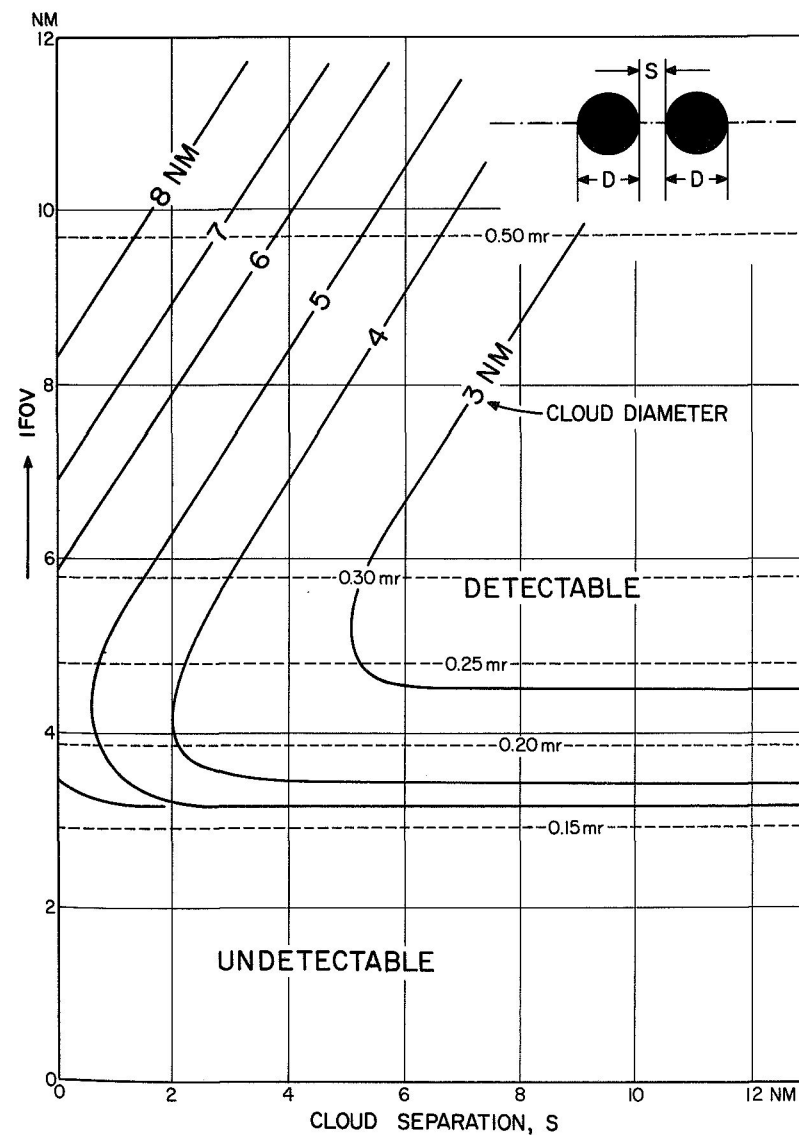


Fig. 27. Detectable and undetectable domains when two model clouds with various diameters were separated up to 12 n.m. in the direction of the scan.

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